# Lysimetry versus Neutron Moisture Meter for Evapotranspiration Determination in Four Soils

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Knowledge of evapotranspiration (ET) is vital for the management of our freshwater resources. One method for determining ET is through the measurement of the soil water balance, where ET is the residual calculated from the change in soil water storage plus precipitation and irrigation and minus drainage and runoff. The objective of this research was to compare the ET calculations where the change in soil water storage was measured using the neutron moisture meter (NMM), or $ET_{NMM}$, vs. using weighing lysimeters ($ET_{LYS}$) in four soils. Cotton (*Gossypium hirsutum* L.) was grown in 2006 and 2007 in weighing lysimeters with NMM access tubes and drainage systems. The soil textures ranged from fine sand to clay loam. The $ET_{NMM}$ was ≤4% of the $ET_{LYS}$ for the clay loam and sandy loam soils, but $ET_{NMM}$ was 8% less than $ET_{LYS}$ in the fine sand due to errors created by the timing of drainage and NMM measurements. At $ET_{LYS}$ amounts <50 mm, the difference between $ET_{LYS}$ and $ET_{NMM}$ for individual measurement intervals could be as much as 28 mm and the average $ET_{NMM}/ET_{LYS}$ ratios as much as 1.20. Beyond 100 mm of $ET_{LYS}$, the average $ET_{NMM}/ET_{LYS}$ ratios became near 1.0 except for the fine sand, where unmeasured drainage out of the NMM sensor zone resulted in an underestimation of ET. When all other soil water balance components were quantified, a field-calibrated NMM accurately determined the change in soil water storage for the calculation of ET in three of the four soils.

Abbreviations: ET, evapotranspiration; $ET_{LYS}$, ET with change in soil water storage determined using lysimetry; $ET_{NMM}$, ET with change in soil water storage determined using the neutron moisture meter; NMM, neutron moisture meter.

The measurement of water evaporation from a surface to the atmosphere, or ET, is fundamental to the management of our freshwater resources. There is a great variety of methods for determining ET, and one hydrologic approach is the soil water balance method.

The soil water balance method is an indirect method, where ET is the residual term in the water balance equation. A simplified form of the water balance equation with ET calculated as the residual is

$$\mathrm{ET} = P + I - R - D \pm \Delta S \qquad [1]$$

where $P$ is precipitation, $I$ is irrigation, $R$ is runoff, $D$ is drainage, and $\Delta S$ is the change in soil water storage in the control volume chosen for application of Eq. [1], all in millimeters (or more explicitly water volume per unit ground area) per unit time. Of the components of the water balance equation, drainage and runoff are often the most difficult to measure and, in certain cases, can be neglected (Holmes, 1984; Rose and Sharma, 1984).

Changes in soil water content need to be determined accurately and for an adequate depth to determine ET (Rose and Sharma, 1984). Many methods exist for the determination of the change in water content of a volume of soil (e.g., neutron thermalization, gravimetric, time domain reflectometry [TDR], and weighing lysimetry). The NMM uses a radioactive source of fast neutrons and a detector of slow neutrons to determine soil water content. To overcome the inherent variability in soil water content in a treatment plot, an adequate volume of soil must be sampled. The NMM measures, at a minimum, a volume of ~14,000 $cm^3$, which is considerably larger than the sampling volumes of most gravimetric methods and TDR (Evett, 2007); however, careful field calibration of the NMM is essential for accuracy (Hignett and Evett, 2002; Evett, 2007). A field-calibrated NMM can reproduce measured volumetric water contents with random errors <0.01 $m^3\ m^{-3}$ (Evett, 2008). The problem of inaccuracy of NMM measurements near the surface can be solved by using a depth-control stand that accurately and reproducibly positions the probe at constant depths below the soil surface. Evett et al. (2003) showed calibrations accurate to <0.01 $m^3\ m^{-3}$ for a probe centered at 10 cm below the soil surface. Van Bavel and Stirk (1967) reported a NMM precision of 1 mm in total water for a 170-cm profile of Adelanto loam (a coarse-loamy, mixed, superactive, thermic Xeric Haplargid) in Arizona.

A lysimeter is a device, typically a tank or a container, that defines a specific boundary to contain soil water and permit measurement of either the soil water balance or the volume of water percolating vertically or its quality (Howell, 2004). For a weighing lysimeter, the change in soil water storage is measured as a change in mass. Lysimeters can provide excellent accuracy and

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temporal resolution in ET measurement (Baker and Norman, 2002). Weighing lysimeters with proper design and electronic measurements can accurately measure ET on a daily time interval without counterbalancing the soil "dead" mass (Howell, 2004).

According to Baker and Norman (2002), the soil water balance method using neutron thermalization for the measurement of the change in soil water content may not provide reasonable results for time scales of a day or less. Van Bavel and Stirk (1967), however, suggested that since the NMM they evaluated had a precision of 1 mm, it could possibly be substituted for a weighing lysimeter to measure daily ET. They compared the $ET_{NMM}$ with the $ET_{LYS}$ at time scales of 2 to 4 d and found a random error of about 2 mm. Wright (1990) compared $ET_{NMM}$ with $ET_{LYS}$ under furrow irrigation, and found that $ET_{NMM}$ underestimated $ET_{LYS}$ by 35% when daily ET rates averaged 3.5 mm during a 50-d period due to losses of water to deep drainage that were unaccounted for. Under sprinkler irrigation, Wright (1990) found much better agreement between $ET_{NMM}$ and $ET_{LYS}$ because irrigations did not wet the soil deeply.

The objectives of this research were (i) to compare the $ET_{NMM}$ with $ET_{LYS}$ for cotton under irrigated and dryland conditions in four soil types, and (ii) to evaluate the accuracy of $ET_{NMM}$ for different time scales and cumulative ET values.

## MATERIALS AND METHODS

### Site Description

The experiment was conducted at the Soil–Plant–Environment Research (SPER) facility, USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX (35°11′ N, 102°6′ W, 1170-m elevation above mean sea level). The SPER facility is located in a 0.25-ha field with a rain shelter facility in which there are 48 weighing lysimeters that contain soils of four different soil series. The lysimeters are 1.0 by 0.75 m and 2.4 m deep and contain monolithic cores to about a 2.3-m depth with a vacuum drainage system in the bottom. The lysimeters are arranged in two pits, with each pit containing two side-by-side rows of 12 lysimeters each. The soil series are randomly located within each pit. There are 12 lysimeters of each soil series. The rain shelter is a metal building 13 by 18 m by 3.7 m high, with a control system that automatically initiates building movement over the lysimeters when about 1 mm of rain is detected. Complete details concerning the monolithic core collection techniques and facility can be found in Schneider et al. (1993) and Tolk et al. (2005).

The lysimeter mass is measured using deck scales (DS3040-10K, Weigh-Tronix, Fairmont, MN). The deck scales are excited and measured by a data acquisition system (CR-7X, Campbell Scientific, Logan, UT). Lysimeter scale mass data were acquired on a 0.1-Hz sampling interval and composited into 30-min means for output. The deck scales were calibrated after installation, and the calibration checked yearly before the cropping season. A typical RMSE of the calibration was 0.09 mm. Details of the calibration procedure were described in Tolk et al. (2005).

The climate at Bushland is typical of the semiarid High Plains, which has a high evaporative demand (about 2600 mm based on Class A pan evaporation) and an average precipitation of about 470 mm. About 70% (350 mm) of the precipitation occurs from May to September, when evaporative potential averages about 1520 mm. Wind direction is predominately from the south–southwest. During the experiment, the lysimeter area was surrounded by similarly cropped cotton for about 30 to 35 m in the prevailing wind direction. About 450 m of dryland grain sorghum [*Sorghum bicolor* (L.) Moench] was south of the SPER facility, and a heterogeneous landscape of grassland, playa, and irrigated and dryland cropland extended >1700 m to the southwest.

### Agronomy

The lysimeters were planted with cotton (Delta and Pine Land Co. 'DP-2280,' Monsanto Co., St. Louis, MO) in 2006 and 2007 at a density of 13 plants $m^{-2}$ in a single row down the center of each lysimeter, which maintained a 0.75-m row spacing with the adjacent lysimeters and surrounding cropped area. In 2006, planting was on Day of the Year (DOY) 145 (25 May) and harvest on DOY 304 (30 October). In 2007, planting was on DOY 157 (6 June) and harvest on DOY 291 (18 October). The lysimeters were fertilized according to recommendations based on soil analyses before planting for each soil. Tillage was done by hand to a depth of about 0.2 m. The lysimeters were hand harvested and the bolls ginned.

Irrigation treatments in 2006 were 100 and 50% replacement of ET and in 2007 were 100, 50, 25, and 0% replacement of ET, with the 50 and 25% replacement of ET treatments simulating deficit irrigation. The lysimeters were irrigated before planting to have either 125 or 200 mm of plant-available water in the anticipated root zone as an additional water treatment in 2006, but were uniformly irrigated to 150 mm of plant-available water in the root zone before planting in 2007. Daily ET of at least two replicates of the fully irrigated treatments served as the basis for the calculation of irrigation treatment amounts. Irrigation was applied using pressure-compensating, point-source drip irrigation emitters.

### Soils

The soil types were Pullman clay loam (a fine, mixed, superactive, thermic Torrertic Paleustoll) from Bushland, TX; Ulysses clay loam (a fine-silty, mixed, superactive, mesic Aridic Haplustoll) from Garden City, KS; Amarillo sandy loam (a fine-loamy, mixed, superactive, thermic Aridic Paleustalf) from Big Spring, TX; and Vingo fine sand (a coarse-loamy, mixed, superactive, mesic Aridic Paleustalf) from Dalhart, TX. The textural analyses by depth are shown in Fig. 1.

The Pullman soil series is a deep, well-drained, very slowly permeable soil that formed in calcareous clayey materials. It has a moderate to high water-holding capacity depending on the depth to the $CaCO_3$ horizons, which begin at about 1 to 1.5 m, and it has a dense Bt layer at about 0.8 m. The Ulysses soil series is a very deep, well-drained, moderately permeable upland soil that formed in calcareous loess and has a high water-holding capacity. The Ulysses soil series typically is classified as a silt loam, but slightly lower silt contents of our soil in its surface layers resulted in its designation as a clay loam. This is within the allowable variation of the series. The Amarillo soil series is a deep, well-drained, moderately permeable soil that formed in calcareous loamy materials and has a moderate water-holding capacity, $CaCO_3$ horizons beginning at about 1 m, and relatively high bulk densities. The Vingo soil series is a deep, well-drained, moderately rapidly permeable soil formed in sandy materials of eolian origin.

### Evapotranspiration Determination by Lysimeter

The 30-min output of the deck scales was used to measure any gain in mass due to water infiltration such as irrigation or precipitation and any loss in mass due to drainage and ET. Drainage was checked periodically using a vacuum pump attached to the drainage system. Because individual drainage amounts were determined by the mass losses of the lysimeter, the vacuum pump was activated by timer to run from 0200 to 0430 h to minimize the effect on the measurement of losses due to evaporation. Irrigations were applied twice weekly before 1100 h and in durations of 1 h or less to minimize the effect on ET due to irriga-

tion evaporation losses. Daily ET was calculated as the change in soil water storage ($\Delta S$) calculated from the difference in the lysimeter mass recorded at 2400 h and 2400 h of the next day, plus any water added as $P$ and $I$ and minus any $D$. Runoff did not occur due to the lysimeter rim. On the day when NMM measurements were made, the 30-min deck scale outputs were summed for that day to synchronize with the NMM measurements. For example, if NMM measurements ended at 1200 h, which represented the termination of the measurement period, deck scale output was summed from 0030 through 1200 h of that day (the first output after midnight was at 0030 h). The deck scale output following the NMM measurement was summed through 2400 h of that day and applied to the next measurement period.

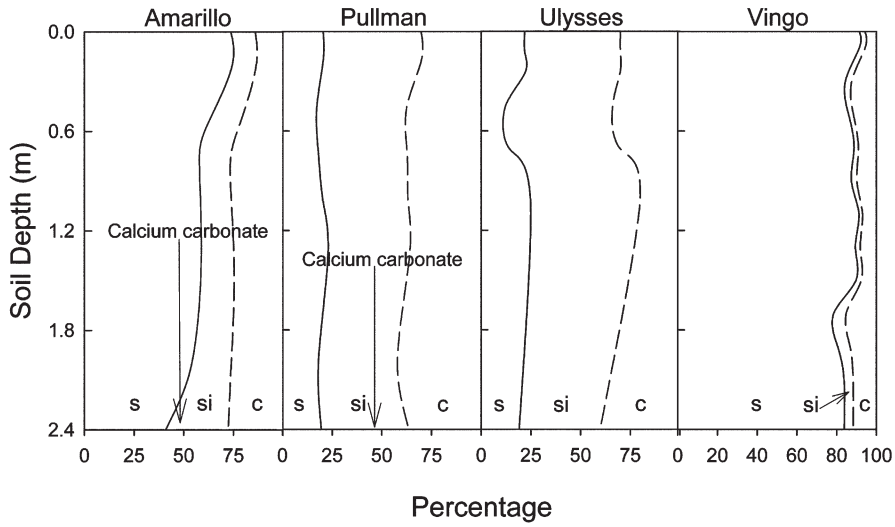


**Fig. 1. Percentages of sand (s), silt (si), and clay (c) by depth in the Amarillo, Pullman, Ulysses, and Vingo soil profiles, with approximate depths of $CaCO_3$ (caliche) indicated for the Amarillo and Pullman soils.**

## Neutron Moisture Meter Calibration

The NMM meter (Model 503 DR, Campbell Pacific Nuclear, Martinez, CA) was calibrated in situ at the monolith collection sites using techniques described by Evett and Steiner (1995) and using a depth control stand (Evett et al., 2003). Data collected from the calibration were aggregated as necessary with respect to soil horizon to avoid combining data from horizons that thermalize neutrons differently, which would have led to unnecessary bias in the calibrations (Greacen, 1981). Calibration equations were explored using linear regression. Separate calibration equations were developed for each major soil horizon with $r^2$ values >0.9 and RMSE values ≤0.01 $m^3\ m^{-3}$ using the count ratio (ratio of the measured count to the mean of several standard counts taken in the NMM probe shield elevated 0.82 m above the soil surface).

The same NMM was used throughout this study. The NMM was originally calibrated at the monolith collection sites, which was in 1989 for the Pullman and Amarillo soils, 1990 for the Ulysses soil, and 2002 for the Vingo soil. Subsequent calibrations were made using the meter in the Pullman soil, with the most recent being performed in 2007. The NMM has been repaired and updated since the original calibrations for the Amarillo and Ulysses soils. The original calibration of the NMM for these soils was updated using procedures described in Hignett and Evett (2002).

## Evapotranspiration Determination by Neutron Moisture Meter

Volumetric soil water contents were determined by neutron thermalization using a profiling NMM in a centrally located tube in each lysimeter. The measurements were taken at 0.20-m increments starting at 0.10 m and ending at 2.10 m for a total measurement depth of 2.20 m. A depth control stand was used to ensure accuracy of the near-surface (0.10-m) reading. Based on the RMSE values of the calibration, the measurement error for the 2.2-m depth did not exceed 22 mm. In actual practice, measurement error is likely to be much less since the data were analyzed in such a way as to avoid bias, leaving the error term to be random and the soil profile water storage, $S$, calculated by integration over the profile depth of individual water contents at all the depths, to be dependent on the random aggregation of positive and negative errors. In such a case, the error is more likely to be of the order of that attributable to one depth increment (200 mm) or 2 mm.

The NMM can determine the water content of the lysimeters and the change in stored water in the lysimeters, but it cannot determine whether changes in stored water are due to evapotranspiration, irrigation, or drainage. Drainage and irrigation amounts were measured separately using the deck scales. Evapotranspiration was then calculated as the change in soil water storage ($\Delta S$) between NMM measurement times, plus any water added as $P$ and $I$ and minus any $D$ (Eq. [1]).

## Statistical Procedures

The daily $ET_{LYS}$ was composited into periods comparable to the NMM measurements for statistical comparison. There were four measurement intervals in 2006 and three measurement intervals in 2007 for a total of 84 measurement intervals among 12 replicates in each soil type used in the analyses. The number of days between NMM measurements was 12, 28, 34, and 60 in 2006 and 14, 46, and 33 in 2007. Data were analyzed using linear regression analysis (Sigmaplot for Windows, version 10, Systat Software, San Jose, CA).

# RESULTS AND DISCUSSION

## Neutron Moisture Meter Readings

Soil water content readings by depth at harvest in 2007 for each soil type are shown in Fig. 2. The error bars at each data point represent ±1 standard deviation at each depth among the 12 replicates of each soil type across the range of irrigation treatments. The soil water content reading nearest to the soil surface was decreased below that used by the crop due to soil water evaporation.

## Precipitation

Generally, a precipitation event of <2 mm will cause the rain shelter to cover the lysimeters. Greater amounts of precipitation can reach the lysimeters in high-intensity rain events. The rain shelter can also fail to move for a rain event due to the activation of the safety switches and misalignment of the rain sensor. In 2006, the lysimeters received about 45 mm in precipitation. Twenty of the 22 precipitation events were <5 mm. About 6 mm was caught by the lysimeters during a high-intensity precipitation and about 13 mm when the rain shelter failed to move. In 2007, the lysimeters received

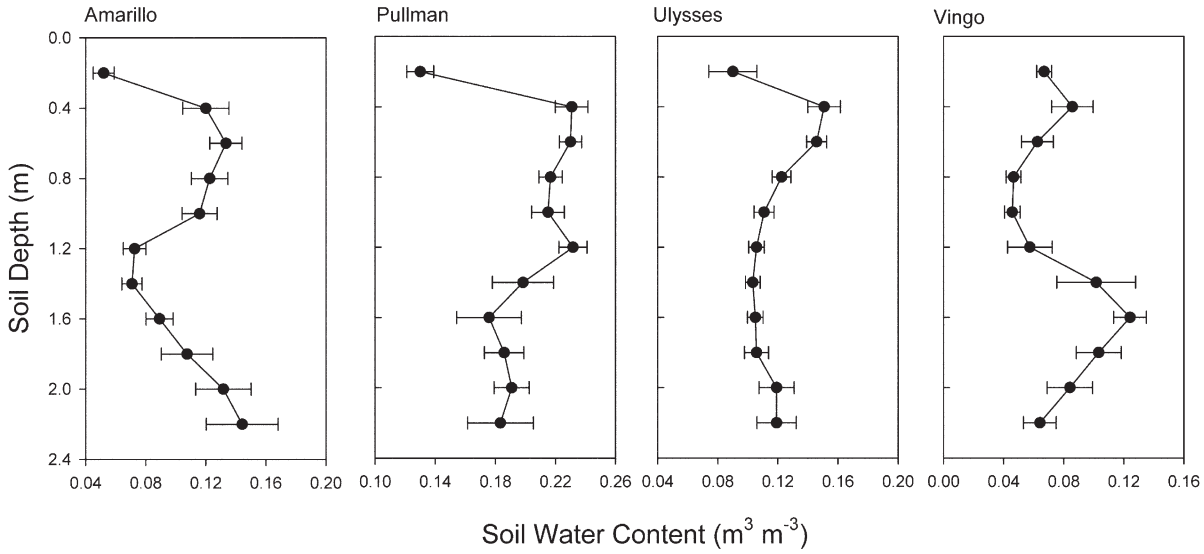


**Fig. 2. Soil water content by depth in the lysimeters as measured by the neutron moisture meter at harvest in 2007 for the Amarillo, Pullman, Ulysses, and Vingo soils. The error bars are ±1 standard deviation among 12 replicate lysimeters for each soil type for each depth across all irrigation treatments.**

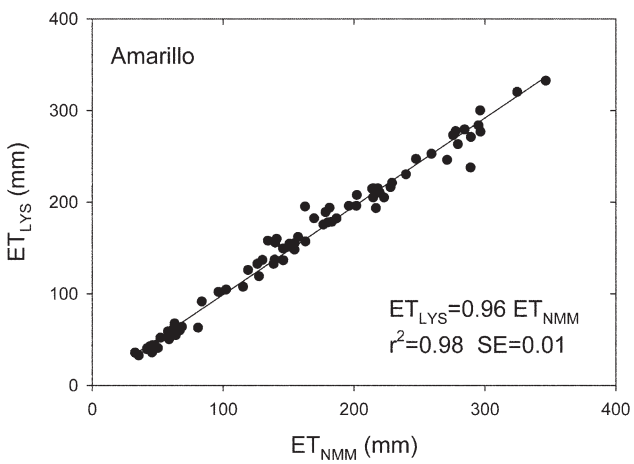


**Fig. 3. The relationship between evapotranspiration (ET) with the soil water storage change determined lysimetrically ($ET_{LYS}$) and by a neutron moisture meter ($ET_{NMM}$) for cotton grown in the Amarillo soil.**

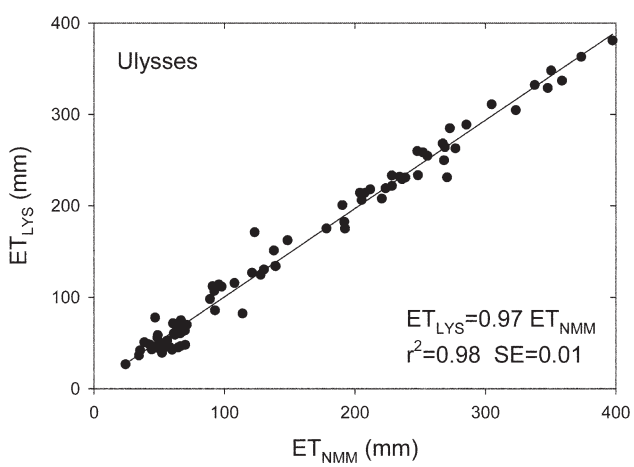


**Fig. 4. The relationship between evapotranspiration (ET) with the soil water storage change determined lysimetrically ($ET_{LYS}$) and by the neutron moisture meter ($ET_{NMM}$) for cotton grown in the Ulysses soil.**

about 66 mm of precipitation. Twenty-three of the 26 events were <5 mm. The lysimeters received about 7 mm in each of two events and about 15 mm in one event when the shelter failed to move.

## Drainage

Drainage occurred in the Vingo soil in all treatments in both years. Drainage amounts were highly variable within treatments (e.g., in 2007, the seasonal drainage from the 0% replacement of ET irrigation treatment ranged from 15 to 111 mm among the replicates). The seasonal drainage was most consistent, averaging 208 (±21) mm, among treatment replicates for the 2006 treatment with the 200-mm initial soil water content and 100% replacement of ET. The same treatment drained in the Amarillo soil, averaging 35 (±13) mm among replicates. Drainage did not occur in the Pullman and Ulysses soil irrigation treatments.

## Evapotranspiration by Lysimeter vs. Neutron Moisture Meter

The $ET_{NMM}$ was larger than the $ET_{LYS}$ by 4% in the Amarillo soil (Fig. 3) and by 3% in the Ulysses soil (Fig. 4) and was similar to $ET_{LYS}$ in the Pullman soil (Fig. 5). All three linear relationships produced an $r^2$ of 0.98 or larger and intercepts that were not significantly different from zero. The $ET_{NMM}$ was larger than the $ET_{LYS}$ by 8% in the Vingo soil, with an increased scatter in the measurements that resulted in an $r^2$ of 0.87 (Fig. 6) and an intercept significantly different from zero. Four data points (marked by × and + in Fig. 6) greatly increased the scatter. The two symbols indicate two consecutive time intervals of NMM readings of two lysimeters. After the first NMM reading, the lysimeter received a substantial amount of irrigation (e.g., 240 mm of irrigation in a 34-d period) that subsequently drained into the drainage system's bed of sand at the bottom of the lysimeter, which was out of the sensor zone of the NMM. At the next reading, the NMM then measured the decrease in water content in the soil profile but not the increase in water content in the drainage bed. In essence, the changes in water content determined by the NMM were accounted for in Eq. [1] as ET rather than $D$ and thus $ET_{NMM}$ was overestimated. When the lysimeter was manually drained during the next time interval, the inclusion

of the measured $D$ in the water balance equation produced either a very small or negative ET number. For example, the two data points marked by + show that the first $ET_{NMM}$ was 310 mm and the second $ET_{NMM}$ was −22 mm. Wright (1990) observed that errors in the NMM method occurred with the vertical movement of water out of the measurement zone in the time interval between readings. By elimination of these four data points, the $ET_{NMM}$ in the Vingo soil was 2% smaller than $ET_{LYS}$, the $r^2$ increased to 0.95, and the intercept was not significantly different from zero. The SE of the slope of the $ET_{NMM}/ET_{LYS}$ relationship for the Amarillo, Pullman, and Ulysses soils was 0.01. These soils typically did not drain. Dropping the four data points only improved the SE of the $ET_{NMM}/ET_{LYS}$ relationship in the Vingo soil to 0.03 because of the remaining scatter among the data points. The marked data points were the extremes in the errors created when drainage was not measured between NMM readings. Smaller errors were created in other measurement periods, which produced the larger scatter in the Vingo soil due to its coarse texture, which drained easily.

Field calibration of the NMM was essential for accuracy (Hignett and Evett, 2002; Evett, 2007). For the Pullman soil, the field calibration produced the relationship of $ET_{LYS} = 1.0\ ET_{NMM}$ with an $r^2$ of 0.99 (Fig. 5). When using the factory calibration, the relationship was $ET_{LYS} = 1.08\ ET_{NMM}$ with an $r^2$ of 0.97 (Fig. 7).

## Increasing Time Scales and Cumulative Evapotranspiration

According to Baker and Norman (2002), the NMM method is better suited to longer measurement intervals because of its inability to measure small changes in water content in a column of soil. The data were analyzed by first dividing individual $ET_{LYS}$ measurements into increments of 50 mm (i.e., 0–49, 50–99 mm, etc.), averaging the $ET_{LYS}$ and the corresponding $ET_{NMM}/ET_{LYS}$ ratios for each period, and producing ±1 standard deviations represented by error bars that were associated with the average $ET_{NMM}/ET_{LYS}$ ratio for each 50-mm increment (Fig. 8).

The largest scatter in the $ET_{NMM}/ET_{LYS}$ ratio occurred in the $ET_{LYS}$ range of 0 to 49 mm, with the tendency of $ET_{NMM}$ to overestimate $ET_{LYS}$ in all soils (Fig. 8). In this range, the Amarillo soil had an average $ET_{LYS}$ of 40 mm, with an average $ET_{NMM}/ET_{LYS}$ ratio of 1.08 (±0.1). The Pullman soil had an average $ET_{LYS}$ of 40 mm and the $ET_{NMM}/ET_{LYS}$ ratio averaged 1.08 (±0.35). The Ulysses soil had an average $ET_{LYS}$ of 44 mm and an average $ET_{NMM}/ET_{LYS}$ ratio of 1.14 (±0.21). The Vingo soil had an average $ET_{LYS}$ of 31 mm and an average $ET_{NMM}/ET_{LYS}$ ratio of 1.20 (±0.32). Examples of the largest differences in the two methods for individual measurements for the $ET_{LYS} < 50$ mm are an $ET_{LYS}$ of 36 mm and $ET_{NMM}$ of 46 mm for the Amarillo soil, an $ET_{LYS}$ of 44 mm and $ET_{NMM}$ of 72 mm for the Pullman soil, an $ET_{LYS}$ of 48 mm and $ET_{NMM}$ of 70 mm for the Ulysses soil, and an $ET_{LYS}$ of 30 mm and $ET_{NMM}$ of 51 mm for the Vingo soil. Holmes (1984) noted that the NMM could just resolve a soil water storage change of 5 mm and that a change of 24 mm would have an error of 10%, with little point in doing NMM measurements more frequently than once in 6 d in the summer. Rose and Sharma (1984) said that experience suggested that it was not feasible to detect changes of <10 mm in soil water content in a profile.

The differences between $ET_{LYS}$ and $ET_{NMM}$ tended to decline as $ET_{LYS}$ increased beyond 50 mm in three of the four soils (Fig. 8). For the range in $ET_{LYS}$ of 50 to 99 mm, the average $ET_{NMM}/$

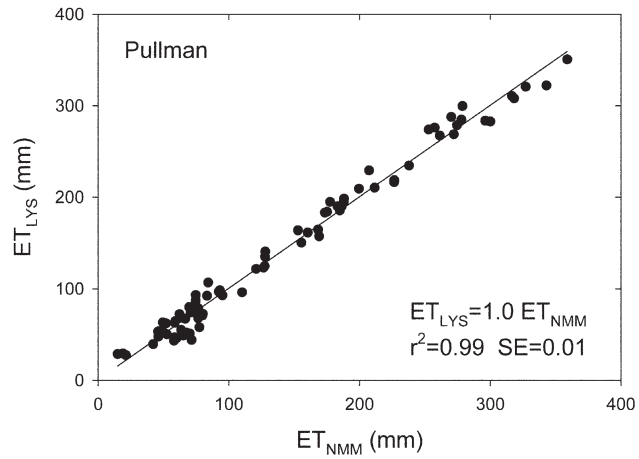


**Fig. 5. The relationship between evapotranspiration (ET) with the soil water storage change determined lysimetrically ($ET_{LYS}$) and by the neutron moisture meter ($ET_{NMM}$) for cotton grown in the Pullman soil.**

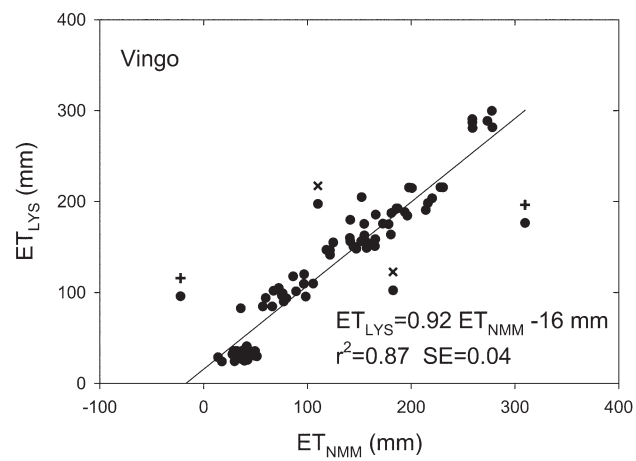


**Fig. 6. The relationship between evapotranspiration (ET) with the soil water storage change determined lysimetrically ($ET_{LYS}$) and by the neutron moisture meter ($ET_{NMM}$) for cotton grown in the Vingo soil. The × and + bracket measurement intervals where drainage was not correctly accounted for in the soil water balance.**

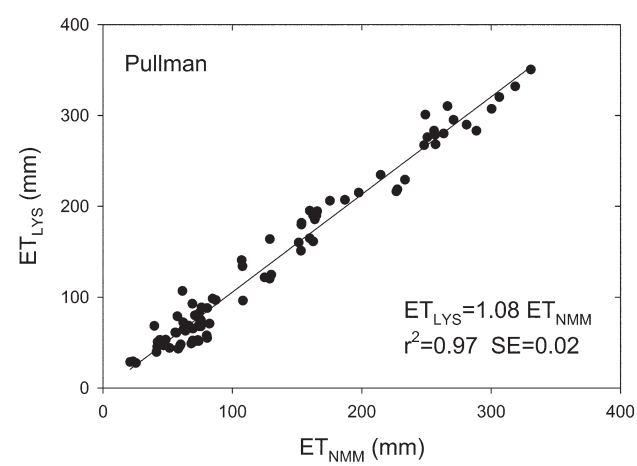


**Fig. 7. The relationship between evapotranspiration (ET) with the soil water storage change determined lysimetrically ($ET_{LYS}$) and by the neutron moisture meter ($ET_{NMM}$) for cotton grown in the Pullman soil using factory calibrations rather than field calibrations for the NMM.**

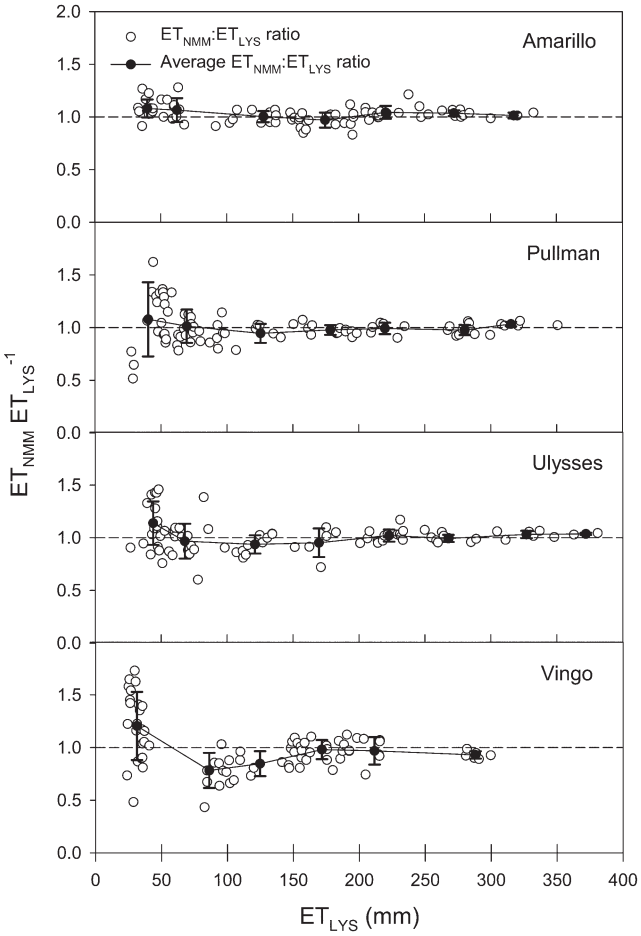


**Fig. 8. Ratio of measured evapotranspiration (ET) with the soil water storage change determined by the neutron moisture meter ($ET_{NMM}$) and lysimetrically ($ET_{LYS}$) as a function of increasing $ET_{LYS}$ for cotton grown in the Amarillo, Pullman, Ulysses, and Vingo soils. The vertical bars at each average $ET_{NMM}/ET_{LYS}$ ratio point represent ±1 standard deviation.**

$ET_{LYS}$ ratio was 1.07 (±0.11), 1.01 (±0.16), and 0.97 (±0.16) for the Amarillo, Pullman, and Ulysses soils, respectively. The average of the $ET_{NMM}/ET_{LYS}$ ratio for the remainder of the range of $ET_{LYS}$ (100+ mm) was 1.01 (±0.06), 0.98 (±0.06), and 0.99 (±0.11) for the Amarillo, Pullman, and Ulysses soils, respectively.

For the Vingo soil, after overestimating $ET_{LYS}$ in the 0- to 49-mm range, the $ET_{NMM}$ underestimated the $ET_{LYS}$ in the 50- to 99-mm range, resulting in an $ET_{NMM}/ET_{LYS}$ ratio of 0.78 (±0.17). The $ET_{NMM}$ method continued to underestimate $ET_{LYS}$ throughout the remainder of the range in $ET_{LYS}$ (100+ mm) (Fig. 8). The largest difference between the two methods among all soil types in this range (100+ mm) was an $ET_{NMM}/ET_{LYS}$ ratio of 0.66 in the Vingo soil that resulted from an $ET_{NMM}$ of 67 mm and a $ET_{LYS}$ of 102 mm.

## CONCLUSIONS

The ET calculated using the soil water balance method with the NMM measuring the change in soil water content was within 4% or less of the ET measured with weighing lysimeters for cotton grown in the Amarillo, Pullman, and Ulysses soils. The NMM was field calibrated, and drainage, irrigation, and precipitation were measured. Using the factory calibration rather than the field calibration resulted in underestimation of $ET_{LYS}$ by the NMM method by 8% in the Pullman soil. The NMM measurement intervals ranged from 12 to 60 d, resulting in a range in $ET_{LYS}$ values. At $ET_{LYS}$ amounts <50 mm, the difference between $ET_{LYS}$ and $ET_{NMM}$ for individual measurement intervals was as much as 28 mm and average $ET_{NMM}/ET_{LYS}$ ratios as much as 1.20. Beyond 100 mm of $ET_{LYS}$, the average $ET_{NMM}/ET_{LYS}$ ratios for the soils were nearer to 1.0, except for the Vingo soil, which was 0.94. Unmeasured drainage out of the NMM sensor zone in the Vingo soil due to its coarse texture biased the $ET_{NMM}$ determination, resulting in most cases in an underestimation of ET. When all other soil water balance components were quantified, a field-calibrated NMM accurately determined the change in soil water storage for the calculation of ET in three of the four soils.

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