Evidence of higher evapotranspiration in croplands than in forestlands in four Mississippi watersheds over the past decade

Ying Ouyang a,⁎, Jia Yang b, Yanbo Huang c, Theodor D. Leininger d, Daryl Chastain e

a USDA Forest Service, Southern Research Station, Center for Bottomland Hardwoods Research, 775 Stone Blvd., Thompson Hall, Room 309, Mississippi State, MS 39762, United States
b Department of Natural Resource Ecology and Management, Division of Agricultural Sciences and Natural Resources, Oklahoma State University, Stillwater, OK 74078, United States
c Genetics and Sustainable Agriculture Research Unit, Crop Science Research Laboratory, USDA-Agricultural Research Service, 810 Highway 12 East, Mississippi State, MS 39762, United States
d USDA Forest Service, Center for Bottomland Hardwoods Research, 432 Stoneville Road, Stoneville, MS 38776, United States
e Sustainable Water Management Research Unit, USDA-Agricultural Research Service, 4006 Old Leland Rd., Leland, MS 38756, United States

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ABSTRACT

Historically, forestlands have been widely recognized to lose more water through evapotranspiration (ET) than croplands. Using remote sensing data from MODIS (Moderate Resolution Imaging Spectroradiometer) with an 8-day temporal and 500 m spatial resolution, we compared the annual ET between croplands and forestlands in the Yazoo River Basin (YRB), a humid subtropical region in Mississippi, USA, over a 21-year period from 2001 to 2021. Based on the Mann-Kendall test, there were significant increasing trends in annual ET for the croplands (τ > 0.44, p < 0.01) but not for forestland over the 21-year period. According to Pettitt’s test, there was an abrupt change (or turning point) in annual ET starting in 2011 for the croplands. Using the time at this turning point (i.e., 2011) along with the Kolmogorov-Smirnov test, we found that there was a very significant difference (α = 0.05) in annual ET between croplands and forestlands with 19% higher ET in the croplands over the 11-year period from 2011 to 2021. This occurred because of increasing irrigated cropland areas in the YRB during this period, providing more water for ET. Our finding on croplands lost more water than forestlands through ET challenge the traditional concept on how forestlands and croplands influence ET.

1. Introduction

Evapotranspiration (ET) is the sum of plant leaf water transpiration and earth surface water evaporation, which contributes the largest amount of water loss from terrestrial surfaces and plays a critical role in hydrological cycle, irrigation scheduling, drainage system development, and water-balance estimation (Allen et al., 1989; Allen et al. 2011; Fisher and Pringle III, 2013; Liu et al., 2013; Oren et al., 1998; Ouyang, 2021; Wilcox et al., 2003). To date, numerous methods have been employed to estimate crop and forest ETs. These include hydrological approaches such as using a soil water balance and weighing lysimeter; micrometeorological approaches such as energy balance and Bowen ratio, aerodynamic, and eddy covariance; and plant physiological approaches such as measuring sap flow or using pressure chamber systems (Allen et al., 1989; Anapalli et al., 2018; Fisher and Pringle III, 2013; Monteith, 1965; Penman, 1948; Rana and Katerji, 2000; Samani and Hargreaves, 1985; Wullschleger et al., 1998). Additionally, remote sensing and machine learning are currently popular in estimating crop and forest ET (Cemek et al., 2023; Mokhtari et al., 2023).

There is currently a general consensus that forestlands lose more and yield less water due to ET than croplands (Guo and Mo, 2007; Hornbeck et al., 1993; Owuor et al., 2016; Verstraeten et al., 2005). Verstraeten et al. (2005) compared the ETs between forest and crop lands using the WAVE (Water and Agrochemicals in soil, crop, and Vadose Environment) model in Belgium. These authors reported that forested lands in Flanders, Belgium evaporated more water than croplands and further argued that the 30-year average ETs were 491 mm for 10 forested stands and 398 mm for 10 croplands. Using the soil-vegetation-atmosphere transfer model along with meteorological data from 1990 to 2003 in 12 ecosystem stations of the Chinese Ecosystem Research Network, Guo and Mo (2007) showed that the mean annual ET followed the order: tropical forest land > subtropical farmland > temperate forest land >...
temperate farmland > grassland. Owuor et al. (2016) synthesized literature reports over land use and land cover (LULC) effects on groundwater recharge and stated that forestlands increase ET in the semi-arid tropical and subtropical regions. Odongo et al. (2019) investigated the effects of LULC and climate change on ET in the Lake Naivasha Basin, Kenya, using the Surface Energy Balance System in conjunction with the Moderate Resolution Imaging Spectroradiometer (MODIS) and European Centre for Medium-Range Weather Forecasts datasets. They found that forestlands and shrublands had the highest annual ET as compared to that of the grasslands and croplands.

In contrast, several studies reported that forestlands may have reduced ET at certain tree ages, management practices, and in certain regions (Liu et al., 2008; Murakami et al., 2000; Ouyang, 2021; Ouyang et al., 2019). Murakami et al. (2000) compared the ET between young (4–7 years) and mature (62–66 years) Japanese cypress (Chamaecyparis obtusa) and found that the mature cypress had less ET. Liu et al. (2008) investigated effects of LULC changes on ET in China. They reported that deforestation increased average ET by 138 mm/year and reforestation decreased average ET by 422 mm/year because most of deforested land was converted to paddy land or irrigated cropland. Recently, Ouyang (2021) compared ET between cropland and forestland in the Yazoo River basin (a humid subtropical region), Mississippi, USA under a changing climate. The comparison was accomplished using the US-Environmental Protection Agency’s Hydrologic and Water Quality System (HAWQS) model along with Mann Kendall statistics (τ) and Kolmogorov-Smirnov (K-S) test. This author reported that there was 10.8 % more water lost in the past from ET, and it was predicted that 42 % more water would be lost in the next 50 years from ET in cropland than in forestland.

The findings from above and numerous other studies underscore the ongoing gaps in our comprehension of ET within crop and forested lands across various climatic regions, such as semi-arid and humid subtropical areas. There exists a pressing need for improved knowledge among water resource managers, farmers, and foresters regarding the impacts of land conversion from forests to croplands and vice versa on ET. This understanding is crucial for the development of site-specific and sustainable water resource management strategies. This study aimed to compare annual ET between croplands and forestlands using data obtained from MODIS. We focused on the Yazoo River basin (YRB), situated in the humid subtropical region of Mississippi, USA. Our specific objectives were to: (1) assess the variations in annual ET, air temperature, and precipitation within croplands and forestlands in the YRB over the past two decades, (2) pinpoint the specific time when annual ET undergoes abrupt change (or turning point) using Pettitt’s test, (3) compare annual ET differences between croplands and forestlands using the K-S test, and (4) identify trends in annual ET in crop and forested lands through the Mann-Kendall analysis.
2. Materials and methods

2.1. Site description

The YRB is the largest river basin in Mississippi (Fig. 1) and is one of the most extensive crop productive regions in midsouth US. Human activities such as clearing forests for croplands, modifying stream channels for navigation and recreation, and pumping groundwater for crop irrigation in the past several decades have resulted in frequent river floods, drying streams, wetland loss, and groundwater table decline in the YRB (Little et al., 1982; Clark and Hart, 2009; MSU Extension Service, 2014; Ouyang et al., 2019). There are two distinct topographies in the YRB with the bluff hills (16,600 km²) in the east and the Mississippi Delta (about 18,200 km²) in the west (Fig. 1). The bluff hills are in the upland of the YRB and primarily occupied by forests with loess and loess-derived alluvium. The Delta area is the lowland of the YRB with clay and fine sand from alluvial deposition of the ancestral Mississippi and Ohio Rivers (Guedon and Thomas, 2004). The YRB has a total drainage area of about 34,800 km² and nine watersheds with cropland, forestland, grassland/wetland, residential, and open water accounting for 35, 37, 18, 6, and 4 % of that area, respectively. The average annual temperature is 18 °C (Southern Regional Climate Center, 1998) and the average annual precipitation is 1290 mm (Berkowitz et al., 2019). Two crop dominated watersheds, i.e., the Big Sunflower River watershed (BSRW, 8172 km²) and Deer Steele River watershed (DSRW, 2133 km²) as well as two forest dominated watersheds, i.e., the Little Tallahatchie River watershed (LTRW, 4270 km²) and Yocona River watershed (YRW, 1927 km²) within the YRB (Fig. 1) were selected for the purpose of this study.

2.2. Data acquisition

In this study, we used remote sensing data for ET from MODIS. Specifically, the 8-day ET data with a 500 m resolution for the BSRW, DSRW, YRW, and LTRW over a 21-year period from 2001 to 2021 were downloaded from MOD16A2 (https://modis.gsfc.nasa.gov/data/download/mod16A2.php, accessed on 28 July 2023). These data are in Tag Image File Format (TIFF), a computer file format used to store raster graphics and image information. The TIFF files were then converted to numerical ET values using a Python script. Upon closer examination of the ET data, it became apparent that some 8-day ET data points were missing within a year, probability due to cloud contamination. Therefore, we decided that it would be best to conduct an annual ET analysis rather than daily and monthly ET analyses with these data.

Air temperature and precipitation data for the BSRW, DSRW, YRW, and LTRW used in this study were originally from the National Climatic Data Center and the National Weather Service of the National Oceanic and Atmospheric Administration. These datasets had already been compiled and pre-loaded into the US-Environmental Protection Agency’s HAWQS model (https://hawqs.tamu.edu/), so we downloaded them directly from HAWQS.

It should be noted that no field measured ET data are available for both the cropland watersheds (i.e., BSRW and DSRW) and forestland watersheds (i.e., LTRW and YRW) used in this study. To validate the usability of the MODIS ET, we used the ground-based approaches, namely the local-estimated and watershed model predicted ETs for comparisons. The local-estimated ETs were obtained using the following empirical equation:

\[ ET = ET_o \times K_c \]  

where \( ET_o \) is the reference ET and \( K_c \) is the crop coefficient (Allen et al., 1989; Feng et al., 2018). The \( ET_o \) was calculated using weather data in Stoneville (within the BSRW), Mississippi (https://beaumont.tamu.edu/climatidata/StateMap.aspx?index=2_14_0_26&name=MISSISSIPPI, accessed on 6 June 2024). Based on this equation and other available data, we were able to obtain the cropland ETs from 2010 to 2015 for the BSRW (Feng et al., 2018), which were used to validate the MODIS ETs. It should also be noted that no local measured or estimated ET data are available for the forestland watersheds used in this study. Therefore, the watershed model predicted ETs from 2010 to 2015 for the YRW (forestland) was used to validate the MODIS ETs for the same period and watershed. Ouyang (2021) investigated ET and water yield in the crop and forest lands of YRB (covered the YRW) under a changing climate, using the HAWQS model that is a customized version of SWAT (Soil and Water Assessment Tool) model. The model predicted ETs from 2010 to 2015 for the YRW were used to validate the MODIS ETs.

2.3. Statistical analysis

Temporal trends of annual ET in crop and forest lands are identified using the Mann-Kendall analysis, which is a nonparametric trend test and is given as (Stuart and Ord, 2010):

\[ S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(X_j - X_k) \]  

with

\[ \text{sgn}(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases} \]  

The mean of \( S \) is zero and the variance is

\[ \sigma = \frac{1}{18} \left( n(n-1)(2n+5) - \sum_{j=1}^{m} t_j^2 (t_j - 1)(2t_j + 5) \right) \]  

where \( n \) is the number of times of measurements, \( m \) is the number of the tied groups in the data set, and \( t_j \) is the number of data points in the \( j \)-th tied group. The Kendall’s S statistic is approximately normally distributed if the following Z-transformation is valid:

\[ Z = \frac{S - \frac{1}{\sigma} \text{if } S > 0 \text{ or } S + \frac{1}{\sigma} \text{if } S < 0}{\sigma} \]  

The statistic \( S \) is closely related to Kendall’s \( \tau \) as:

\[ \tau = \frac{S}{C} \]  

with

\[ C = \left( \frac{1}{2} n(n-1) - \frac{1}{2} \sum_{j=1}^{p} t_j^2 (t_j - 1) \right)^{1/2} \left( \frac{1}{2} n(n-1) \right)^{1/2} \]  

Comparison of the annual ET differences between the croplands and forestlands is estimated using the K-S test. This test is based on the empirical cumulative distribution function (ECDF). Given \( N \) ordered data points \( Y_1, Y_2, \ldots, Y_N \), the ECDF is defined as (Solari, 1967):

\[ E_N = \frac{n(i)}{N} \]  

where \( E_N \) is the ECDF, \( n(i) \) is the number of points less than \( Y_i \) and the \( Y_i \) are ordered from smallest to largest value. The K-S test is calculated as (Solari, 1967):

\[ D = \max_{1<i<N} \left| \frac{i-1}{N} - \frac{i}{N} F(Y_i) \right| \]  

where \( F \) is the theoretical cumulative distribution.

An abrupt change (or turning point) of annual ET in the croplands...
and forestlands is detected by a Pettitt test. The Pettitt test is a statistical tool used to identify a single abrupt change point in the mean or median values of a time series dataset (Pettitt, 1979). The null hypothesis, or no change, \( t = T \) is tested against the alternative hypothesis, or change, \( 1 \leq t < T \) with the non-parametric K statistic (Pettitt, 1979):

\[
K_t = \max_{1 \leq t \leq T} |U_{t,T}| = \max(K_t^+, K_T^+)
\]

with

\[
U_{t,T} = \sum_{t \leq j \leq T} \text{sgn}(u_j - u_t)
\]

and

\[
\text{sgn}(x_j - x_i) = \begin{cases} 
1 & \text{if } (u_j - u_i) > 0 \\
0 & \text{if } (u_j - u_i) = 0 \\
-1 & \text{if } (u_j - u_i) < 1 
\end{cases}
\]

where \( T \) is the end time of a dataset, \( t \) is the time when the time series variable \( u \) has an abrupt change point, and \( K_t^+ \) or \( K_T^+ \) is statistically significant if the value \( p \) is < 0.05 in this study. If the null hypothesis is rejected, the time \( t \) is the point of the abrupt change. All these statistical analyses were accomplished in the R-statistical platform.

3. Results and discussion

3.1. MODIS ET validation

To develop users’ confidence, the MODIS ETs were validated using the ground-based approaches, namely the local-estimated and watershed model predicted ETs. The local-estimated ETs were available for cropland of the BSRW, whereas the watershed model predicted ETs were obtainable for forestland of the YRW. A comparison of the annual ETs between the MODIS and the local-estimated for the BSRW is shown in Fig. 2a. With \( R^2 = 0.9738 \) and \( p < 0.0001 \), we concluded that the ETs from MODIS were close to those from local-estimated. A visual plot between the MODIS and local-estimated ETs from 2010 to 2015 (Fig. 2b) further confirmed our conclusion.

Similar results were obtained for the forestland. That is, the MODIS annual ETs matched the model predicted annual ETs well for the YRW with \( R^2 = 0.9958 \) and \( p < 0.0001 \) (Fig. 2c). This finding was further strengthened with a visual comparison of the annual ETs between MODIS and model-predicted over the period from 2010 to 2015 (Fig. 2d). Results validated that the MODIS ETs obtained in this study were usable.

3.2. Annual ET in the most recent two decades

Changes in annual average ET in croplands (BSRW and DSRW) and forestlands (LTRW and YRW) over a 21-year period from 2001 to 2021 are shown in Fig. 3. In general, the annual ET varied with years and locations in the croplands (Fig. 3a). For instance, the annual ETs were 419 mm in the BSRW and 748 mm in the DSRW in 2003 but were 1376 mm in the BSRW and 691 mm in the DSRW in 2014. These variations occurred primarily because precipitation and air temperature, which are the major factors governing annual ET, varied with years in the croplands (Figs. 4a and 5a). Additionally, variations in crop cultural practices such as changing crop species, land area, and irrigation rate between the two watersheds could also be a factor. Similar variations in annual ET were observed for the forestlands. That is, the annual ET varied with years in the forestlands (Fig. 3b) for the same reasons, i.e., the precipitation and air temperature varied with years (Figs. 4b and 5b) in addition to variations in crop cultural practices.

Comparison of Fig. 3a and Fig. 3b reveals that variations in annual ET were somewhat smaller in forestlands than in croplands. For
example, the range of annual ETs was from 419 to 1376 mm with a difference of 957 mm (i.e., $1376 - 419 = 957$) in croplands, but was from 630 to 950 mm with a difference of 320 mm (i.e., $950 - 630 = 320$) in forestlands. The standard deviation was 224 mm in the croplands but 73 mm in forestlands. The latter was about 3 times less than the former.

We attributed the large variations of annual ET in croplands to the large changes in cropland management practices such as crop productions (e.g., shifting soybean and cotton to corn and rice that need more water), irrigation, and harvesting.

Differences in average annual ET, air temperature, and precipitation between croplands and forestlands over the 21-year period are shown in Figs. 3c to 5c. The annual averages had the following orders: (1) DSRW (845 mm, cropland) > YRW (817 mm, forest land) > BSRW (790 mm, cropland) > LTRW (787 mm, forest land) for ET (Fig. 3c); (2) YRW (1514 mm) > LTRW (1513 mm) > DSRW (1462 mm) > BSRW (1430 mm) for precipitation (Fig. 4c); and (3) DSRW (17.9 °C) > BSRW (17.1 °C) > YRW (15.9 °C) > LTRW (15.7 °C) for air temperature (Fig. 5c). Results indicated that there were differences in average annual ET, air temperature, and precipitation between croplands and forestlands. However, our K-S tests on ET, air temperature and precipitation reveal that such differences were statistically not significant.

### 3.3. Annual ET in the last decade

Based on Pettitt’s test, no abrupt changes in average annual ET were observed for forestlands (i.e., YRW and LTRW) over the 21-year period from 2001 to 2021, while abrupt changes in annual ET were detected starting in 2011 at $p = 0.001$ for croplands (BSRW and DSRW) over the same period. Therefore, the annual ET dataset from 2011 to 2021 (i.e., the last decade) was further used to compare the ET difference between croplands and forestlands. It is reported that cropland irrigation in the region increased in 2007 (Lo and Pringle, 2021), but the turning point for cropland ET increase in the same region happened in 2011. The discrepancy occurred because the turning point and the increasing point are two different concepts. The ET turning point, identified by the Pettitt’s test, referred to an abrupt change point, while the cropland irrigation increased from 2007 was gradually and not an abrupt changing point.

Changes in annual average ET in croplands (BSRW and DSRW) and forestlands (LTRW and YRW) from 2011 to 2021 are shown in Fig. 6a. While no significant difference for the 21-year (2001–2021) annual ET was found between croplands and forestlands, such a difference was very significant at $\alpha = 0.05$ for the 11-year annual ET based on the K-S test (Table 1). As shown in Fig. 6b, the annual average ET was in the following order: BSRW (999 mm, cropland) > DSRW (957 mm, cropland) > YRW (844 mm, forestland) > LTRW (795 mm, forestland). Overall, the annual average ET was 19% (i.e., $(999+957)/2 - (844+795)/2 = 100\% - 19\%$) greater in croplands than in forestlands. This finding contradicts the prevailing scientific concept that forestlands produce more ET than croplands (Guo and Mo, 2007; Hornbeck et al., 1993; Owuor et al., 2016; Verstraeten et al., 2005). Since there were no significant differences in average annual precipitation (Fig. 4c) and air temperature (Fig. 5c) between croplands and forestlands, a possible explanation for the elevated annual ET in croplands could be the increase in irrigation of cropland areas over the last 11 years. Lo and Pringle (2021) performed a quantitative review of crop irrigation

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**Fig. 4.** Annual average precipitation over the 21-year period from 2001 to 2021 in croplands (a) and forestlands (b). A box plot of the annual average precipitation in the croplands and forest lands (c). The values in the parenthesis are all years’ average precipitation.

**Fig. 5.** Annual average air temperature over the 21-year period from 2001 to 2021 in croplands (a) and forestlands (b). A box plot of the annual average air temperature in croplands and forestlands (c). The values in the parentheses are all average annual air temperatures.
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development in the YRB using the Farm and Ranch Irrigation Survey and Census of Agriculture survey data. These authors reported that irrigated croplands in Mississippi have increased from 5500 km² in 2007 to 7400 km² in 2017 and 81% of irrigated croplands are primarily in the Mississippi Delta (covered the BSRW and DSRW). Massey et al. (2017) measured the crop irrigation rate in the Mississippi Delta for a 12-year period from 2002 to 2013 and reported the average irrigation rates across all years were 9200, 3100, 2800, and 1800 m³/ha for rice, maize, soybean, and cotton, respectively. Based on the studies of Lo and Pringle (2021) and Massey et al. (2017), the volume of water used for irrigation increased to 260,541,667 m³ in 2017 from 193,645,833 m³ in 2007 in the Mississippi Delta. In other words, irrigated water volume increased about 26% over the 11-year period from 2007 to 2017. Such a large increase in irrigation water volume would cause an increase in soil water availability and thereby increase cropland ET. In contrast, little to no irrigated area was increased in forestlands in the recent 11 years. As such, ET in the croplands surpassed that of forestlands. This conclusion was consistent with that reported by Ouyang (2021). Using the HAWQS model, this author compared ET between cropland and forestland in the YRB under a changing climate and showed that over the long-run, forestland reduced ET as compared to that of cropland.

3.4. Annual ET trend

Temporal trends of annual ET in croplands and forestlands over a 21-year period from 2001 to 2021 are shown in Fig. 7, which were detected using the Mann Kendall analysis. In the Mann Kendall analysis, the τ value measures the relationship between average annual ET and year. If the τ value is zero, no relationship exists between the average annual ET and year, when the τ value is 1 (or −1), there is a perfect relationship (with positive τ for an increasing trend and negative τ for a decreasing trend). The p value measures a trend, when the p value is ≤ 0.05, there is a monotonic trend (Mangiafico, 2016).

Over the 21 years from 2001 to 2021, there were significant increasing trends in annual ET (τ = 0.61, p = 0.0001 for the BSRW and τ = 0.44, p = 0.006 for the DSRW) in croplands (Fig. 6a and 6b), while there were no significant trends in forestlands (Fig. 6c and 6d). As there were no differences in air temperature and precipitation in both the croplands and forestlands over the 21-years period, we attributed the

Fig. 6. Annual average ET over the 11-year period from 2011 to 2021 in croplands and forestlands (a) and a box plot of the annual average ET in croplands and forestlands (b). The values in the parentheses are average annual ET.

Table 1

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<th>Critical Value (n-scaled)</th>
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<td>BSRW (cropland) vs. DSRW (cropland)</td>
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<td>0.500</td>
<td>&lt; 0.607</td>
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</table>

Fig. 7. Trends of annual average ET over the 21-year period from 2001 to 2021 in the BSRW (a), DSRW (b), LTRW (c), and YRW (d).
increasing trends in annual ET in croplands to an increase of irrigated cropland areas as discussed in Section 3.2. Results indicate that cropland irrigation played a critical role in changing the average annual ET rate in this region characterized by intensive crop production and a humid subtropical climate.

Precautions should be taken regarding the ET data from MODIS, which could under- or over-estimate annual ET, depending on study locations (Conrad et al., 2007; Ha et al., 2015; Heinsch et al., 2006). There is no eddy covariance measured ET data available for forestslands and only limited and short-term eddy covariance measured ET data may be available for croplands in the YRB. This makes the comparison of annual ET between croplands and forestslands much more difficult using the incomplete eddy covariance measured ET.

It should be noted that our finding of higher ET in croplands compared to forestslands is site-specific for the watersheds in the YRB, where areas of irrigated cropland have increased dramatically in recent years. Nonetheless, our finding demonstrates that forestslands may not always lose more water than croplands and point to the need for further research on this subject.

4. Conclusions

Variations in annual ET were smaller in forestslands than in croplands. The standard deviation in croplands was about 3 times greater than in forestslands. The large variations in annual ET in croplands occurred due to large changes in cropland management practices such as crop production, irrigation, and harvesting.

There were no statistical differences in annual ET, air temperature and precipitation between the croplands and forestslands over the 21-year period from 2001 to 2021. In contrast, a very significant difference was observed in annual ET between the croplands and forestslands over the 11-year period from 2011 to 2021. The annual average ET was 19 % greater in the croplands than in the forestslands in the 11-year period, which occurred because of increased areas of irrigated cropland. Our results demonstrate that under intensive irrigation, croplands can lose more water than forest lands.

No temporal trend in annual ET was found in the forestslands over the 21-year period from 2001 to 2021, but a very significant increasing trend in annual ET was detected in the croplands during the same period.

The research finding that croplands lost more water than forestslands through ET challenges our traditional understanding of how forestslands and croplands influence ET in the humid subtropical region. It will provide critical water resource managers, foresters, and farmers in the region and around the world for developing better agricultural water management strategies. It should be noted that physiologival investigations of ET between croplands and forestslands have not been carried out. Further study is therefore warranted to tackling this issue.

CRediT authorship contribution statement

Theodor D. Leininger: Writing – review & editing. Daryl Chastain: Writing – review & editing. Ying Ouyang: Writing – review & editing. Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. Jia Yang: Writing – review & editing. Yanbo Huo: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

References


