Research Article

Potential Evapotranspiration Reduction and Its Influence on Crop Yield in the North China Plain in 1961–2014

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Climate change has caused uneven changes in hydrological processes (precipitation and evapotranspiration) on a space-temporal scale, which would influence climate types, eventually impact agricultural production. Based on data from 61 meteorological stations from 1961 to 2014 in the North China Plain (NCP), the spatiotemporal characteristics of climate variables, such as humidity index, precipitation, and potential evapotranspiration (ET0), were analyzed. Sensitivity coefficients and contribution rates were applied to ET0. The NCP has experienced a semi-arid to humid climate from north to south due to the significant decline of ET0 (∼−13.8 mm decade⁻¹). In the study region, 71.0% of the sites showed a “pan evaporation paradox” phenomenon. Relative humidity had the most negative influence on ET0, while wind speed, sunshine hours, and air temperature had a positive effect on ET0. Wind speed and sunshine hours contributed the most to the spatiotemporal variation of ET0, followed by relative humidity and air temperature. Overall, the key climate factor impacting ET0 was wind speed decline in the NCP, particularly in Beijing and Tianjin. The crop yield in Shandong and Henan provinces was higher than that in the other regions with a higher humidity index. The lower the humidity index in Hebei province, the lower the crop yield. Therefore, potential water shortages and water conflict should be considered in the future because of spatiotemporal humidity variations in the NCP.

1. Introduction

Hydrological processes and crop water requirements have been modified by climate change on local, regional, and global scales [1, 2]. The modification of climate change has coincided with surface air temperature increase.

In the hydrological cycle, actual evapotranspiration (ET) and potential evapotranspiration (ET0) played important roles [3], particularly in soil evaporation and crop transpiration, eventually impact crop productivity. ET is measured as the quantity of water evaporating from an area under existing atmospheric conditions [4]. ET is controlled by two processes occurring simultaneously: evaporation from the soil and transpiration from the leaf surface [5]. ET0 is calculated as the maximum quantity of water that can be lost as water vapor in a given climate, by a continuous, extensive stretch of vegetation covering the ground when there is no shortage of water [6]. ET0 is determined by the meteorological conditions and the surface type [7]. Because ET0 is computed from precipitation, temperature, relative humidity, wind speed, and sunshine hours [8–10], any change in these variables is likely to change the ET0. Furthermore, these changes created more benign or stressful conditions for ET0 [11, 12]. ET0 had a significant impact on the availability of water resources [13], consequently influencing agricultural productivity. Plant growth planning
often requires information on ET₀ [14, 15] to estimate crop transpiration. Therefore, the study of ET₀ under climate change has become an interesting research issue to scientists around the world. Also, it is important to identify the changes in ET₀ on a regional scale.

The humidity index (K), change in precipitation, and ET₀ were applied to estimate dry-wet variations. Previous research studies on climate type only considered the influence of temperature and precipitation [16, 17] without including the influence of relative humidity, solar radiation, wind speed, and sunshine hours. Therefore, to understand the changing characteristics of climate variations, it is important to integrate water resource management. Furthermore, K can be applied to predict model scenarios that would persist in critical agricultural areas. Therefore, assessing ET₀ and K distribution would explain the relationships between climate change and hydrological processes. This would lead to reasonable water regulation and management to maintain the ecohydrological system.

In the NCP, summer maize (Zea mays L.) represents 33% of the national grain yield, while winter wheat represents 50% of the national grain yield [18]. Increasing temperature and decreasing precipitation are likely to reduce the yields of several primary crops over the next two decades [19]. Water shortage would be aggravated in the main production belt of North China [20, 21]. Bergamaschi et al. [22] indicated that crop yields would reduce by 10–20% up to 2050 because of warming and drying. Hence, understanding the hydrological distribution in these regions is critical for managing agricultural water resources and adjusting the planting pattern.

At present, there are few studies on the spatiotemporal variations in climate type by integrating the input (precipitation) and output (evapotranspiration) of atmospheric water vapor in the NCP. Therefore, the objectives of this study were to (1) quantify the changes in spatial and temporal variations in ET₀ and K in the NCP from 1961 to 2014, (2) quantitatively explain the reasons for the changes in ET₀ by analyzing the sensitivity coefficients and contribution rates, and (3) analyze the relationship between ET₀ and the crop yield. The results might be useful to agricultural planning and layout.

2. Materials and Methods

2.1. Study Area and Data. The study area, located in the NCP (31°–43°N and 110°–123°E), has a warm, temperate monsoon climate. The precipitation changes significantly in summer. The main crops are summer maize and winter wheat. The mean annual temperature and average annual precipitation were 13.0°C and 586 mm, respectively [23]. The soil has a silt-loam texture in the cultivated layer in general. This study was based in Beijing, Tianjin, Hebei province, Henan province, and Shandong province.

In this study, daily meteorological data from January 1961 to December 2014 were obtained from 60 stations in the NCP (Table 1). These data contained daily mean, minimum and maximum temperature, sunshine hours, wind speed, precipitation, and relative humidity provided by the National Climatic Centre of China Meteorological Administration (http://cdc.cma.gov.cn). The wind speed at 10 m height was converted to wind speed at 2 m height using the wind profile relationship introduced in Allen et al. [24], as shown in equation (1). The observed dataset has been subjected to strict quality and homogenization control. The geographical location of the stations is shown in Figure 1.

\[
u_2 = u_2 \cdot \frac{4.87}{\ln (67.8z - 5.42)}
\]

where \(u_2\) is the wind speed at 2 m above the ground surface (m·s⁻¹), \(u_z\) is the wind speed at \(z\) m above the surface (m·s⁻¹), and \(z\) is the height of measurement above the ground surface (m).

2.2. Data Analyses

2.2.1. Estimation of Humidity Index (K). Humidity index is the ratio of precipitation to potential evapotranspiration and is calculated by

\[
K = \frac{P}{ET_0}
\]

where \(P\) is the daily precipitation (mm·d⁻¹) and ET₀ is the daily potential evapotranspiration (mm·d⁻¹). The classification of climate region based on humidity index is listed in Table 2 [25].

\[
ET_0 = \frac{0.408(R_n - G) + \gamma 900/T + 273U_2(e_a - e_i)}{\Delta + \gamma (1 + 0.34U_2)}
\]

where \(R_n\) is the net radiation at the surface, MJ·m⁻²·d⁻¹, \(G\) is soil heat flux density, MJ·m⁻²·d⁻¹, \(\gamma\) is the psychrometric constant, kPa·°C⁻¹, \(T\) is the mean daily air temperature, °C, \(U_2\) is the wind speed at a height of 2 m, m·s⁻¹, \(e_a\) is the saturation vapor pressure, kPa, \(e_i\) is the actual vapor pressure, kPa, and \(\Delta\) is the slope of the saturated water-vapor pressure curve, kPa·°C⁻¹. The computation of all data required for calculating ET₀ followed the method and procedure given in Chapter 3 of FAO-56 [24].

2.2.2. Sensitivity Analysis and Sensitivity Coefficient. Sensitivity analysis of the ET₀ equation is an effective way to analyze the effect of meteorological factors on ET₀ [26]. Previous studies showed the usage of nondimensional relative sensitivity coefficients to explain climate variables influence on ET₀ [27]:

\[
S_{Vi} = \lim_{\Delta V_i \to 0} \frac{\Delta ET_0}{ET_0} \left( \frac{V_i}{\Delta V_i} \right) = \frac{\partial ET_0}{\partial V_i} \frac{V_i}{ET_0}
\]

where \(S_{Vi}\) is the sensitivity coefficient of the \(i\)th climate variable, ET₀ is the potential evapotranspiration, mm·d⁻¹, \(\Delta ET_0\) is the daily change of ET₀, \(V_i\) is the \(i\)th climate variable, and \(\Delta V_i\) is the change of \(V_i\). A positive/negative \(S_{Vi}\) of a variable indicated that ET₀ would increase/decrease as climate variables. The greater the \(S_{Vi}\), the greater effect of the climate factor on ET₀.
Table 1: Geographic characteristic information of each meteorological station in the study.

| No. | Province | Site       | Latitude (°) | Longitude (°) | Elevation (m) |
|-----|----------|------------|--------------|---------------|---------------|
| 1   | Beijing  | Huairou    | 40.72        | 116.55        | 487.9         |
| 2   | Beijing  | Miyun      | 40.38        | 116.87        | 71.8          |
| 3   | Beijing  |            | 39.80        | 116.47        | 31.3          |
| 4   | Beijing  | Zhangbei   | 41.15        | 114.70        | 1393.3        |
| 5   | Beijing  | Weixian    | 39.83        | 114.57        | 909.5         |
| 6   | Hebei    | Shijiazhuang| 38.03        | 114.42        | 81.0          |
| 7   | Hebei    | Xingtai    | 37.07        | 114.50        | 77.3          |
| 8   | Hebei    | Fengning   | 41.22        | 116.63        | 661.2         |
| 9   | Hebei    | Weichang   | 41.93        | 117.75        | 842.8         |
| 10  | Hebei    | Zhangjiakou| 40.78        | 114.88        | 724.2         |
| 11  | Hebei    | Huaihai    | 40.40        | 115.50        | 536.8         |
| 12  | Hebei    | Chengde    | 40.98        | 117.95        | 385.9         |
| 13  | Hebei    | Zunhua     | 40.20        | 117.95        | 54.9          |
| 14  | Hebei    | Qinglong   | 40.40        | 118.95        | 227.5         |
| 15  | Hebei    | Qinhuangdao| 39.85        | 119.52        | 2.4           |
| 16  | Hebei    | Langfang   | 39.12        | 116.38        | 9.0           |
| 17  | Hebei    | Tangshan   | 39.67        | 118.15        | 27.8          |
| 18  | Hebei    | Leting     | 39.43        | 118.88        | 10.5          |
| 19  | Hebei    | Baoding    | 38.85        | 115.52        | 17.2          |
| 20  | Hebei    | Raoyang    | 38.23        | 115.73        | 19.0          |
| 21  | Hebei    | Huanghua   | 38.37        | 117.35        | 6.6           |
| 22  | Hebei    | Nangong    | 37.37        | 115.38        | 27.4          |
| 23  | Hebei    | Anyang     | 36.05        | 114.40        | 62.9          |
| 24  | Hebei    | Xinxiang   | 35.32        | 113.88        | 73.2          |
| 25  | Henan    | Sannengxia | 34.80        | 111.20        | 409.9         |
| 26  | Henan    | Luoshi     | 34.05        | 111.03        | 568.8         |
| 27  | Henan    | Mengjin    | 34.82        | 112.43        | 333.3         |
| 28  | Henan    | Luanchuang | 33.78        | 111.60        | 750.3         |
| 29  | Henan    | Zhengzhou  | 34.72        | 113.65        | 110.4         |
| 30  | Henan    | Xuchang    | 34.03        | 113.87        | 66.8          |
| 31  | Henan    | Kaifeng    | 34.78        | 114.30        | 73.7          |
| 32  | Henan    | Xixia      | 33.30        | 111.50        | 250.3         |
| 33  | Henan    | Nanyang    | 33.03        | 112.58        | 129.2         |
| 34  | Henan    | Baofeng    | 33.88        | 113.05        | 136.4         |
| 35  | Henan    | Xihua      | 33.78        | 114.52        | 52.6          |
| 36  | Henan    | Nanyang    | 32.61        | 113.67        | 153.0         |
| 37  | Henan    | Zhumadian  | 33.00        | 114.02        | 82.7          |
| 38  | Henan    | Xinyang    | 32.13        | 114.05        | 114.5         |
| 39  | Henan    | Shangqiu   | 34.45        | 115.67        | 50.1          |
| 40  | Henan    | Gushi      | 32.17        | 115.62        | 42.9          |
| 41  | Henan    | Huiminxiang| 37.48        | 117.53        | 11.7          |
| 42  | Henan    | Gaoqing    | 37.12        | 117.88        | 122.3         |
| 43  | Henan    | Changdao   | 37.93        | 120.72        | 39.7          |
| 44  | Henan    | Longkou    | 37.62        | 120.32        | 4.8           |
| 45  | Shandong | Chengshantou| 37.40        | 122.68        | 47.7          |
| 46  | Shandong | Chaoyang   | 36.23        | 115.67        | 37.8          |
| 47  | Shandong | Jinan      | 36.60        | 117.05        | 170.3         |
| 48  | Shandong | Qiyuan     | 36.18        | 118.15        | 305.1         |
| 49  | Shandong | Yantai     | 37.23        | 120.49        | 48.6          |
| 50  | Shandong | Weifang    | 36.75        | 119.18        | 22.2          |
| 51  | Shandong | Qingdao    | 36.07        | 120.33        | 76.0          |
| 52  | Shandong | Haiyang    | 36.77        | 121.18        | 40.9          |
| 53  | Shandong | Gunzhow    | 35.57        | 116.85        | 51.7          |
| 54  | Shandong | Feixian    | 35.25        | 117.95        | 121.2         |
| 55  | Shandong | Juxian     | 35.58        | 118.83        | 107.4         |
| 56  | Shandong | Rizhao     | 35.43        | 119.53        | 36.9          |
| 57  | Shandong | Linyi      | 34.96        | 118.51        | 36.2          |
| 58  | Shandong | Jixian     | 40.17        | 117.45        | 5.1           |
| 59  | Shandong | Tianjin    | 39.08        | 117.07        | 2.5           |
| 60  | Shandong | Tanggu     | 39.05        | 117.72        | 4.8           |
2.2.3. Calculation of Attribution Rate. The attribution rate $G_{vi}$ is used to link the climate variable to $ET_0$:

$$G_{vi} = S_{vi} \times R_{vi},$$

where $G_{vi}$ is the contribution of the $i$th climate variable to $ET_0$, $S_{vi}$ is the sensitivity coefficient, and $R_{vi}$ is the relative change rate for the $i$th climate variation, which was given by equation (5). The meaning of $G_{vi}$ is the same as $S_{vi}$.

In this study, $S_{vi}$ and $G_{vi}$ for daily air temperature, solar radiation, relative humidity, and wind speed were estimated to quantify the contribution of each factor to the variation of $ET_0$.

2.2.4. Climate Trend. Climate tendency rate ($\text{Trend}_{vi}$) was calculated by the least square method:

$$X_i = at + b, \quad (t = 1, 2, 3 \ldots n),$$

where $X_i$ is the $i$th climate variation, $t$ is the time in years, $a$ is the regression coefficient, $10^\alpha a$ is the climate tendency rate, and $b$ is the constant parameter.

### Table 2: Humidity index ($K$).

| Humidity index | Climate region       |
|----------------|----------------------|
| $K < 0.03$    | Extremely arid climate region |
| $0.03 < K < 0.2$ | Arid climate region     |
| $0.2 < K < 0.5$ | Semiarid climate region |
| $0.5 < K < 1.0$ | Semihumid climate region |
| $K > 1.0$    | Humid climate region   |

3. Results

3.1. Annual and Spatial Variation and Tendency of Humidity Index. The humidity index ($K$) showed an upward trend from north to south, changing from 0.34 to 1.20 (Figure 2(a)), which indicated that the climate of the region varied from semiarid to humid from north to south. The climate in Northwest and mid-west Hebei was semiarid, while that in South Henan was humid, with $K$ above 1. The other regions had semihumid climate, with $K$ ranging from 0.5 to 1.0.

The tendency rate of $K$ was $-0.005$ decade$^{-1}$ ($P = 0.63$), which showed a slight drying trend from south to north (Figure 2(b)). Thirty-five percent of the sites (total = 60) mainly distributed in southern NCP had a tendency rate of $K$ above 0, which indicated that these regions were wet. The other sites with a tendency rate of $K$ below 0, especially East Shandong and North Hebei, were dry with a tendency rate of $K$ below $-0.01$ decade$^{-1}$.

3.2. Interdecadal Changes in Precipitation and $ET_0$. The tendency rate of precipitation was $-12.4$ mm decade$^{-1}$, which indicated a downward trend. The abrupt decline in precipitation tendency rate was mainly observed in Southeast Hebei and Southeast Shandong (Figure 3(a)). Only 10.0% of all the sites had a tendency rate of precipitation over 0.

The $ET_0$ tendency rate was $-13.5$ mm decade$^{-1}$ (Figure 3(b)), which showed a downward trend from 1961 to 2014. The $ET_0$ tendency rate was significant at the 0.05 level in 71.0% of the sites, especially in mid-east Hebei and mid-south Shandong.

3.3. Sensitivity Coefficient of Temperature ($S_T$), Relative Humidity ($S_{RH}$), Sunshine Hours ($S_{SHEL}$), and Wind Speed ($S_{WS}$) to $ET_0$. The sensitivity coefficients varied from 0 to 0.15.
which meant that ET₀ increased with temperature. Sᵣ in the southeast was higher, especially in the Henan province, while it peaked in the mid-region, such as North Shandong, Beijing, Tianjin, and North Hebei. Sᵣ varied from −0.70 to −0.19 (Figure 4(b)), which indicated that ET₀ decreased as the relative humidity increased. The spatial distribution of Sᵣ showed a downward trend from south to east. The Sᵣ was higher in East Shandong, with an absolute value above 0.5. In South Hebei and Beijing, the absolute value of Sᵣ was below 0.4. The Sᵣ in all regions was above 0, with a mean value of 0.18 (Figure 4(c)). The Sᵣ showed an upward trend from north to south. Sᵣ ranged from 0.10 to 0.31 (Figure 4(d)) and showed a downward trend from north to south. The Sᵣ in the northern part of the region, e.g., North Hebei, Beijing, and Tianjin, was above 0.21, while in South Henan, it was below 0.18.

3.4. Climate Factor Attribution Rate to ET₀ on Annual and Spatial Scales. Gᵣ was applied in this study to indicate the relative change in ET₀ resulting from each meteorological factor. The attribution rate of air temperature to ET₀ (GᵥT) ranged from −0.5% to 4.0% (Figure 5(a)). GᵥT in the northern and eastern parts of the NCP was over 1%, while it was less than 1% in the other regions. The attribution rate of relative humidity to ET₀ (GᵥRH) ranged from −4.7% to 10.1% (Figure 5(b)). GᵥRH in North Hebei and Southwest Shandong was below 0. The attribution rate of sunshine hours to ET₀ (GᵥSH) ranged from −8.4% to 0.2% (Figure 5(c)). GᵥSH was above 0 in only one site. The spatial distribution of GᵥSH showed a downward trend from north to south. The attribution rate of wind speed to ET₀ (GᵥWS) ranged from −19.1% to 4.9% (Figure 5(d)). The highest absolute value of GᵥWS was in Beijing and Tianjin.

The attribution rate of air temperature and relative humidity to ET₀ was positive, which indicated that ET₀ increased with an increase in these two climate factors. However, the mechanisms of GᵥT and GᵥRH were different. GᵥT was positive when the sensitivity coefficient was positive and the tendency rate (0.24°C decade⁻¹) of air temperature increased (Figure 6(a)). GᵥRH was positive when the sensitivity coefficient was negative and the tendency rate
(0.44 decade$^{-1}$) of relative humidity decreased (Figure 6(c)). The attribution rate of sunshine hours and wind speed was negative, which indicated that the change in the two climate factors decreased ET$_0$. The attribution rate of climate factor to ET$_0$ was in the following order: wind speed > sunshine hour > relative humidity > air temperature.

4. Discussion

The change in climate types was due to the sensitivity to various meteorological variables and their attribution to ET$_0$ in the NCP. ET$_0$ was most sensitive to relative humidity, which had a negative effect. This was consistent with the study by Hu et al. [28] in Northeast China. The factor that impacted ET$_0$ significantly varied depending on the location. Huo et al. [3] indicated that ET$_0$ was very sensitive to 2 m wind speed and relative humidity in Northwest China. In southern Spain, ET$_0$ was sensitive to air temperature and radiation in the warmer season and to 2 m wind speed in cooler seasons [29]. In Australia, temperature was found to be the most important factor for ET$_0$ but the second-most important factors differed between dry and humid catchments [30]. Yang et al. [31] showed that the sensitivity of ET$_0$ to climate factors varied from low elevations to high elevations. The sensitivity of ET$_0$ to climate factors is regional variation because climate conditions and climate factors differ with regional variation [30, 31]. In this study, wind speed reduction was the main reason for the decline in ET$_0$ from 1961 to 2014. However, the climate tendency rate was low and resulted in a relatively low attribution rate.

In general, warm climates led to an increase in evaporation and evapotranspiration. However, the observation of pan evaporation rate has been declined in most parts of the world in the past several decades [8, 9, 32, 33], which is called the pan evaporation paradox phenomenon [34]. Although the air temperature significantly increased at the rate of 0.24°C decade$^{-1}$, the effect of decrease in wind speed and sunshine hours was greater than that of the increase in air temperature, which led to a significant decline of ET$_0$ in the NCP. This pattern of variations is in agreement with the findings of Dinapashoh et al. [36] in North-West Iran where most of the stations selected (86% of the sites) also showed increasing trends in ET$_0$ between 1997 and 2016. However, Hou et al. [37] revealed that temperature was the key variable.
Figure 5: Spatial distribution of attribution rate to ET₀ of the main meteorological elements from 1961 to 2014. (a) Temperature. (b) Relative humidity. (c) Sunshine hours. (d) Wind speed.

Figure 6: Tendency rate of temperature (a), relative humidity (b), sunshine hours (c), and wind speed (d) from 1961 to 2014 in the NCP.
contributing to increasing ET$_0$ due to its sensitivity to ET$_0$ and the significant increase trend.

Agriculture accounts for at least 90% of the total water use in the arid and semiarid regions [38]. An important way to alleviate water stress is to improve agricultural water management. Comprehensively understanding an agro-hydrological process lays a foundation for minimizing agricultural water use. In the presence of a shallow water table, groundwater provides an important source for crop water use in arid and semiarid regions [39, 40], which impact crop productive. Climate type depended on the rate of change of precipitation and ET$_0$. The important issue involves the evaluation of drought impacts on agriculture. Crop yields and drought occurrence statistics are closely related [42, 42], but consistency analysis of drought trends derived from humidity index and agricultural drought survey is sparse. Crop yield increased significantly ($P \leq 0.001$) in the study area (Figure 7), in accordance with $K$ in each area. The crop yield was greater in Shandong and Henan province, with a $K$ of 0.70 and 0.77, compared with that in Tianjin, Beijing, and Hebei (Table 3). The lowest $K$ (0.53) was in Hebei province, along with the lowest crop yield. Therefore, regional water balance should be considered and drought or flood risk might be reduced in these areas. China has investigated agricultural drought area for decades, so it is important to investigate the degree that $K$ and ET$_0$ with agricultural drought surveys, especially in their climatic trends.

### 5. Conclusions

The NCP has experienced a semiarid to humid climate from north to south based on the humidity index due to the slight change in precipitation and the significant decline of ET$_0$ on annual and spatial scales. In the study region, 71.0% of the sites showed a "pan evaporation paradox" phenomenon. ET$_0$ was the most sensitive to relative humidity, particularly in East Shandong, followed by wind speed. The dominant cause of ET$_0$ decline was wind speed, with the highest attribution rates, particularly in Beijing and Tianjin. The higher the humidity index in Shandong and Henan province was, the higher the crop yield was. The lower the humidity index in Hebei province was, the lower the crop yield was. It is necessary to analyze the influence of ET$_0$ on crop yield at various crop growth stages.

### Data Availability

The data used to support the findings of this study have been deposited in the 3691421data-2019.xls repository and are included within the article.

### Disclosure

The first author is Wanlin Dong.

### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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