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Does climate change affect wheat productivity and water demand in arid regions? Case study of Egypt

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ABSTRACT

The study investigates the effects of climate change on wheat productivity (Y_w) and crop water requirements (CWR) across different regions in Egypt, highlighting the potential threat to the country's wheat self-sufficiency goals. Data spanning from 1987 to 2019 from lower, middle, and upper Egypt, as well as areas outside the Nile valley of Egypt, underwent both parametric and non-parametric statistical analysis to discern trends in climate parameters and their impact on wheat growth stages. Findings reveal a significant increase ($P \leq 0.05$) in Y_w across the study areas, attributed to effective self-sufficiency strategies, with increases of 0.61, 0.60, 0.59, and 0.56 Mg ha^{-1} per decade in middle Egypt, outside the Nile valley, lower, and upper Egypt study zones, respectively. Although the observed significant increase in Y_w, results revealed a significant negative relationship between Y_w, maximum air temperature (T_{max}), minimum air temperature (T_{min}), and wheat growing degree days (GDD) depending on the study zone and the wheat growth stage. The study notes a more significant rise in T_{min} than T_{max}, adversely affecting Y_w, particularly in upper Egypt, where T_{min} rose by 0.43 °C per decade. CWR rose by ~12 % in lower Egypt, ~15 % in middle and upper Egypt, and ~18 % outside the Nile valley between 2009 and 2019 compared to 1987–1997 under the best farming conditions. Wheat in middle Egypt showed resilience to climatic change, whereas in the Nile valley zone, the node development stage was significantly sensitive to T_{max} fluctuations. In lower Egypt, T_{min} and wheat GDD changes during anthesis and physiological stages significantly negatively impacted Y_w. The study suggests that wheat self-sufficiency strategies in Egypt and similar climates should start to incorporate air temperature and GDD considerations. Recommendations include adopting heat, drought, and disease-resistant wheat varieties and focusing on expanding wheat cultivation in other zones rather than upper Egypt to cope with climate change.

1. Introduction

Water availability is critical for agricultural productivity, especially in regions with arid climatic conditions. Climate change in arid regions can jeopardize food production and security in these regions [1–3]. Egypt, an arid Mediterranean country, faces both water scarcity and food security challenges. The competition for water in Egypt is intensifying due to several factors, such as the increasing population growth rate and the Nile water development projects by the upstream countries [4,5]. The annual population growth rate in Egypt was two percent in 2019. Population in Egypt is expected to increase from 100 million in 2019 to ~160 million by 2050 [6], which add more pressure on conventional water demand. The anticipated negative effect of climate change and global warming might exacerbate the pressure on limited water resources, as reported by the sixth report of the Intergovernmental Pannel for Climate Change - IPCC [7]. The air temperatures in Egypt are projected to rise by at least 0.1 °C per decade [6] to 1.5 °C and higher [7]. As a result, water demand in agriculture will increase due to higher reference evapotranspiration (ET_o[1]) and crop evapotranspiration (ET_c[2]) [7–9]. In consequence, the agricultural sector in Egypt is at high risk giving its annual water consumption of ~80–85 % of its water resources [10] and its dependence on one water source, the Nile River, which

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[1] ET_o: Reference evapotranspiration.
[2] ET_c: Crop evapotranspiration.

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contributes with ~97 % of its conventional water sources [6].

On the other hand, wheat (*Triticum aestivum*) is a main crop in the global and Egyptian food basket [11,12]. Wheat was grown on about 221 million hectares in 2019 worldwide and yielded about 766 million tones [13]. Egypt's wheat production in 2022 was ~9 million tons from 1.52 million hectares of land [13,14]. It accounts for one-fifth of the world's food, the first source of protein in developing countries [15], contributes with ~10 % of the total agricultural production value, and forms ~20 % of the agriculture imports in Egypt [16]. Wheat is grown in Egypt from November to mid-April under irrigated conditions, with relatively stable yield [17,18]. To meet the expected food needs and challenges, Egypt plans to raise its wheat self-sufficiency from 47 % in 2021 to 70 % in 2030 [19]. However, the water shortage problem and the climate change vulnerability of wheat are the main obstacles in Egypt.

A systematic review of the literature revealed inconsistent findings on the impact of air temperature and climate warming on wheat production depending on crop variety and the climate conditions of the study area. Several studies reported that the temperature during the early spring is a critical factor for the wheat crop that influences its growth rates and phenological development [20–22]. Variations in air temperature could negatively affect crop productivity [11,12,23–27]. Wheat photosynthesis rate declines at temperatures above 30°C–35 °C [28], leading to lower yield production [29–31]. Another study on the effect of air temperature on wheat production reported that the optimal temperature range for wheat growth is ~16–26 °C, and temperatures above 40 °C impair crop development and growth [32]. Other studies estimated that a one-degree Celsius increase in air temperature above 15 °C would result in a 5.0–8.5 % reduction in wheat yield [12,31]. However, Abdalla et al. [22] in their study on the potential impact of changes in air temperature on wheat yield in the central US using the CERES-Wheat model indicated that the negative impact of increasing air temperature is mitigated if the minimum air temperature (T_{min}[3]) increases more than the maximum air temperature (T_{max}[4]). The authors categorized the relationship between air temperature and wheat yield into three types. The first one is the direct impacts that affect how well the wheat survives winter, fulfills its cold requirement, and copes with drought stress. The second one is the phenological impacts that control how long the crop stays in the productive and vegetative stages, and the third is the physiological impacts that modulate the processes of photosynthesis and evapotranspiration (ET[5]).

Moreover, air temperature indirectly influences wheat production through the crop growing degree days (GDD[6]), which account for both minimum and maximum air temperatures. GDD is calculated by averaging the T_{max} and T_{min} and subtracting the base temperature (the threshold below which crop development ceases) [33,34]. Klepper [20] estimated that the wheat crop requires ~80–120 GDD to produce one leaf after emergence. Thus, it is possible to determine the number of leaves at any stage by the accumulated GDD during that stage. However, GDD may be affected by other factors such as rainfall (P[7]), windspeed, and extreme heat wave events, which may alter the GDD requirement for the same number of leaves under different conditions [20].

It is essential to secure a balance between Egypt's self-sufficiency plans for wheat production and limited water resources for more sustainable food security. In addition, awareness of climate variability and trends would benefit planners and policymakers in water and food security sectors for more sustainable mitigation planning and management [35]. Therefore, a comprehensive study on the effects of T_{min}, T_{max}, P, and GDD on wheat productivity is needed in Egypt, a Mediterranean arid climate country, to understand their relationships.

The impacts of climate change on global agricultural productivity were examined using a variety of approaches, such as artificial intelligence, neural networks, modeling, and remote sensing [36–40]. These techniques have demonstrated their reliability and validity for studying the impact of climate change on crop productivity, but they also have some limitations. For instance, most of them are complex and require elevated levels of expertise to implement. Moreover, these parametric methods rely on the assumption of normality, which is often violated by climatic data, especially precipitation [35,41,42]. Furthermore, most yield prediction models in response to climate change need prior calibration to a specific area before being used [43,44]. This is because of the variations in soil characteristics [45], climatic conditions, plant [46], and agricultural practices, which exist among different areas.

On the other hands, the non-parametric methods are widely applied to detect historical and future monotonic trends [47] in various parameters across different fields, such as hydrology [42,48–51], climate change [35,41,52], environmental pollution [53–55], oceanography [56,57], and agriculture [58–63]. For instance, Brisson et al. [60] employed linear regression analysis with time trend to investigate the causes of wheat productivity decline in France. They attributed the observed reduction in wheat yield to heat stress during grain filling and drought events during stem elongation stages. Similarly, Musa et al. [58] examined the association between wheat yield and T_{max} and T_{min} in Sudan for the period 1970–2018 using Mann-Kendall (MK[8]) trend test with Sen's slope (S_s[9]). They estimated the magnitude of change in each parameter and its impact on wheat yield. They found a negative correlation between wheat yield and T_{min} above 20 °C and the T_{max} in some regions. Another example in the study by Licker et al. [59] that quantified the winter wheat yield in France and Russia for thirty consecutive years (1981–2010). They applied the non-parametric trend test to assess the change in air temperature and wheat GDD. They concluded that climate change was likely responsible for the observed reduction in wheat yield by 11 % during the study period.

Despite the growing number of studies that applied non-parametric trend and regression analyses to understand the impacts of climate change on wheat productivity, no such research has been conducted in Egypt, to the best of our knowledge, where wheat is a strategic crop for food security and self-sufficiency plans. Therefore, utilizing the MK non-parametric trend test and Sen's slope estimator delves into the variations and trends within climate parameters (T_{min}, T_{max}, P) and wheat-related variables (GDD, ET_o, ET_c) across Egypt's wheat-producing zones. The MK-test's null hypothesis (H_o)[10] posits no trend in the observed data, while its alternative hypothesis (H_a)[11] suggests a possible upward or downward trend. The study aims, as well, to apply the regression analysis to establish a relationship between wheat productivity and the tested climate variables to understand their potential effect on wheat productivity and water demand during the last three decades (1987–2019). The regression analysis' H_o assumes no significant influence of the predictor variables on the wheat productivity. The current study offers valuable insights for decision-makers, scholars, and agriculturists in Egypt and similar Mediterranean climates to strategize against climate change's negative effects and adjust wheat self-sufficiency plans in the context of the current water scarcity problems.

2. Materials and methods

2.1. Study area

Egypt, an arid Mediterranean country in the Middle East and North

[3] T_{min}: Minimum air temperature.
[4] T_{max}: Maximum air temperature.
[5] ET: Evapotranspiration.
[6] GDD: Growing degree days.
[7] P: Rainfall.
[8] MK: Mann-Kendall.
[9] S_s: Sen's slope.
[10] H_o: The null hypothesis.
[11] H_a: The alternative hypothesis.

Africa (MENA)[12] region, is selected as the study area. It is in the northeast of Africa between 22°-32°N and 24°-36°E. It is situated south of the Mediterranean Sea and surrounded by the Red Sea from the East, Sudan from the south, and Libya from the West. The study area has a Mediterranean dry climate in the north and a continental climate in the south with limited rainfall [64]. Egypt generally consists of four administrative zones: Lower Egypt, Middle Egypt, Upper Egypt, and outside the Nile Valley of Egypt, as presented in Fig. 1.

Annual rainfall levels in Egypt are too low (<100 mm) and concentrated in the autumn and winter seasons. It varies from an average of 12.35 mm in lower Egypt to 6.03, 2.16, and 0.83 mm outside the Nile valley, middle Egypt, and upper Egypt, respectively. The monthly average T_{max} and T_{min} vary from 31.14 to 26.35 °C in lower Egypt; to 35.96–24.93 °C (outside the Nile valley), 40.55–24.74 °C (middle Egypt), and 40.59–28.14 °C in upper Egypt, respectively.

2.2. Research dataset source

We collected data on wheat area and yield from 1987 to 2019 from the Egyptian Ministry of Agriculture and Land Reclamation (MALR) and the Food and Agriculture Organization of the United Nations (FAO). The wheat crop in Egypt is growing during the winter season from November to mid-April [17,65] each year. The wheat productivity (amount of wheat yield per unit area), expressed as megagrams per hectare (Mg ha^{-1}), was computed by dividing the total grain yield by the total area under wheat cultivation in each study zone per year. We used wheat productivity to avoid the potential effect of wheat horizontal expansion on our findings.

The daily records of minimum, maximum, and average air temperatures (°C), solar radiation (MJ m^{-2} day^{-1}), dew point (°C), relative humidity (%), and wind speed (m s^{-1}) at 2 m height were collected from thirty weather stations across Egypt, as shown in Fig. 1. The coordinates and locations of each station are given in the supplementary material. The data source was the Central Laboratory for Agricultural Climate (CLAC-MALR), Egypt. The data spanned from 1986 to 2019, which matched the World Meteorological Organization (WMO) recommendation of a 30-year standard reference period for assessing climate change [66].

2.3. Data processing and analyses

2.3.1. Crop parameters calculations

For estimating ET_o, ET_c, and GDD, we used climate data for the wheat crop season. We utilized the ET_o calculator software [version 3.2, FAO, Rome, Italy] to calculate ET_o based on the climatic variables of T_{max}, T_{min}, average temperature, relative humidity, dew point, wind speed, and solar radiation following the method of Allen et al. [67]. We employed equation (1) for calculating the monthly seasonal wheat ET_c for the same time series (1987–2019) according to Allen et al. [67].

$$ET_c = ET_o \times k_c \tag{1}$$

where K_c[13] is wheat crop factor [dimensionless]

The accumulated heat requirements for wheat development represented in GDD for each season during 1987–2019; is computed following Equation (2) [68].

$$GDD = \left(\frac{T_{max} + T_{min}}{2}\right) - T_b \tag{2}$$

where T_b[14] is the base temperature of 5 °C [68] at which wheat development stops [34].

[12] MENA region: Middle East and North Africa region.

[13] K_c: Wheat crop factor (dimensionless).

[14] T_b: Base temperature at which the crop development stops (°C).

2.3.2. Non-parametric trend tests

The non-parametric statistical analysis was performed using Minitab 21.3 statistical software (©2022 Minitab, LLC.). The significance level was set at p ≤ 0.05 and p ≤ 0.001, while p ≥ 0.05 was regarded as nonsignificant.

The MK-trend non-parametric test was applied to examine the monotonic trend in the monthly climate variables (T_{min}, T_{max}, P) and seasonal crop-related variables (ET_o, ET_c, GDD, and wheat productivity) during 1986–2019. The null hypothesis (H_o) of the MK-test is that the observed parameter has no trend, and the alternative hypothesis (H_a) is that the observed parameter has an upward or downward trend. The MK statistic (K_m) is calculated as follows:

$$K_m = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(X_j - X_i) \tag{3}$$

Where:

$$sign(X_j - X_i) = \begin{cases} 1, if\ X_j - X_i > 0 \\ 0, if\ X_j - X_i = 0 \\ -1, if\ X_j - X_i < 0 \end{cases} \tag{4}$$

Where X_i denotes the observation at time i, and X_j denotes the observation at time i+1. A positive K_m value ($K_m > 0$) implies an increasing trend, meaning that the later observations are greater than the earlier ones, and vice versa for a negative K_m value ($K_m < 0$). The mean of K_m equals zero and the variance of K_m (σ^2) is defined as:

$$\sigma^2 = \frac{1}{18}\left\{n \bullet (n-1) \bullet (2n-5) - \sum_{j=1}^{p} t_j \bullet (t_j - 1) \bullet (2t_j + 5)\right\} \tag{5}$$

Where t_j is the total data points number of the jth group in the data set, p is the total number of t-groups, and n is the number of observations.

The positive or negative monotonic trend in MK-test is evaluated by computing Z statistic as defined in equation (6).

$$Z = \begin{cases} \frac{K_m - 1}{\sqrt{\sigma^2}}, if\ K_m > 0 \\ 0, if\ K_m = 0 \\ \frac{K_m + 1}{\sqrt{\sigma^2}}, if\ K_m < 0 \end{cases} \tag{6}$$

where positive Z indicates an increasing trend in tested data and negative Z indicates a decreasing trend in the tested series.

Hamed [42] pointed out that the presence of significant autocorrelation in the data can lead to false positive or negative monotonic trends when applying the MK-test. To avoid this problem, he suggested a pre-whitening procedure that can transform an autocorrelated time series into an uncorrelated one before conducting the MK-test. The first step is to estimate the sample lag-1 autocorrelation coefficient (r1[15]) as described in equation (7) and check if it falls between the upper and lower limits in the condition $\frac{-1-1.96\bullet(n-2)^{0.5}}{n-1} \le r1 \le \frac{-1+1.96\bullet(n-2)^{0.5}}{n-1}$. If r1 lies within the critical values, the null hypothesis of no autocorrelation is accepted and the time series is considered independent at P ≤ 0.05, thus no pre-whitening is necessary. Otherwise, the time series exhibits autocorrelation, which requires pre-whitening before conducting the MK-test as explained in step 2.

$$r1 = \frac{\frac{1}{n-k}\sum_{i=1}^{n-1}(X_i - \overline{X}) \bullet (X_i + 1 - \overline{X})}{\frac{1}{n}\sum_{i=1}^{n}(X - \overline{X})^2} \tag{7}$$

Where n is the number of observations, X_i is the value of observation X at time I, and $\overline{X}$ is the sample average of the time series.

[15] r1: Autocorrelation coefficient.

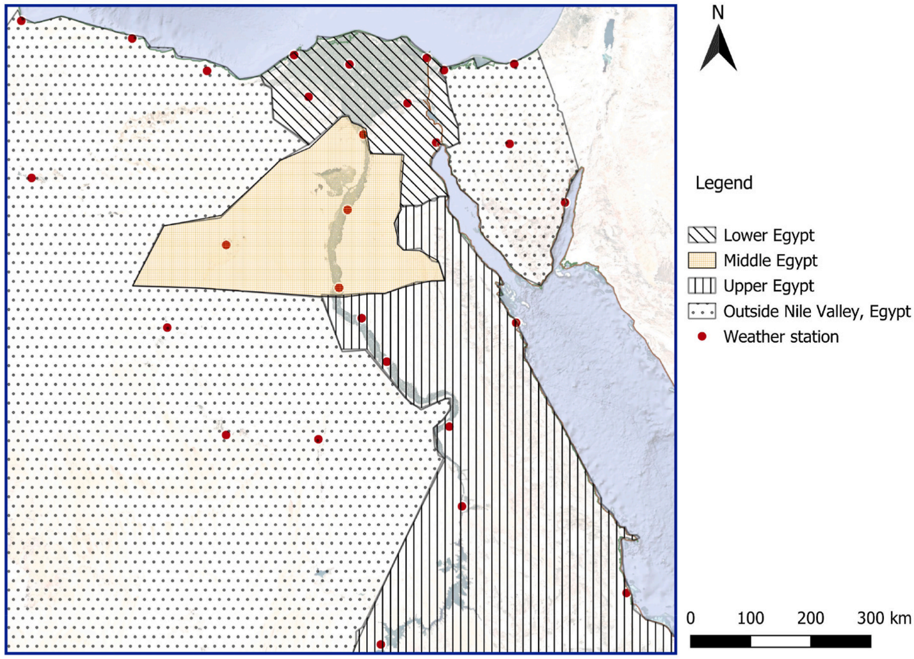

Fig. 1. Location of the main four study zones and the distribution of selected meteorological stations.

Step 2: Remove the trend in time series as described in equation (8).

$$X_i^{'} = X_i - (m \bullet i) \quad (8)$$

Where $m = median\left[\frac{X_j - X_i}{j - i}\right]$ for all i < j

Step 3: Obtain the residual series by removing the lag-1 computed in equation (7).

$$B_i^{'} = X_i^{'} - r1 \bullet X_{i-1}^{'} \quad (9)$$

Then add the $(m \bullet i)$ value to the residual series to obtain the pre-whitened series B_i ready for running the MK-test following equation (10):

$$B_i = B_i^{'} + (m \bullet i) \quad (10)$$

The Sen's slope method (equation (11)) is a non-parametric technique for estimating the magnitude of the trend in a time series of measurements. It involves computing the slope as the difference between two measurements divided by the corresponding difference in time for all pairs of observations in the series [69].

$$S_s = \begin{cases} E^{'}_{\frac{N+1}{2}}, N \ \ is\ odd \\ \frac{1}{2}\left(E^{'}_{\frac{N}{2}} + E^{'}_{\frac{N+2}{2}}\right), N\ is\ even \end{cases} \quad (11)$$

where $E^{'} = \frac{X_b - X_c}{b - c}$, since E′ is the slope between X_b and X_c at time b and c, respectively for b > c, and N is the slope observations $\left[N = \frac{n \bullet (n-1)}{2}\right]$.

The equations used for estimating MK and Sen's slope non-parametric trend tests were adopted following [35,41,42,48,52,69].

2.3.3. Multilinear regression analysis

The stepwise multi linear regression (SWMLR[16]) analysis was performed using SPSS version 15 statistical program (SPSS Inc., 1989–2006). The significance level was set at $p \leq 0.05$ and $p \leq 0.001$, while $p \geq 0.05$ was regarded as nonsignificant. The SWMLR analysis was conducted between wheat productivity (Y_w)[17] and T_{min}, T_{max}, P, and GDD on seasonal basis and for each month during the crop growth season from November to mid-April. The objective was to determine which climate variable will significantly affect wheat productivity on seasonal basis and at each growth stage. The SWMLR is given by equation (12).

$$Y_w = a + \beta_1 \bullet GDD + \beta_2 \bullet P + \beta_3 \bullet T_{min} + \beta_4 \bullet T_{max} + e \quad (12)$$

Where the dependent (Y_w) is explained by the regressors (GDD, P, T_{min}, and T_{max}). a[18] is the Y_w axis intercept, β_1, β_2, β_3, and β_4[19] are the regression coefficients for GDD, P, T_{min}, and T_{max}, respectively. e[20] is the random error that denotes the residual derived from $e = O_i - P_i$.(where O_i[21] is the observed Y_w and P_i[22] is the predicted one by the model).

To analyze the impact of the tested variables in equation (12) on wheat productivity, we excluded the potential long-term effects of other factors that may affect wheat productivity during the study period, such as on-farm management practices and crop varieties. Before running the SWMLR analysis, we applied the first differences approach [59] to the climate variables and wheat productivity. This technique compares the year-to-year changes in climate variables with the year-to-year changes in wheat productivity. We calculated the year-to-year changes in a variable by subtracting its value for one year from the previous year in the continuous time series. This step allows us to capture the annual climate and yield variations from 1987 to 2019. To evaluate the fit of the significant models, we used the coefficient of determination (R^2[23]), which indicates how well the regressors estimate the dependent variable. A high value of R^2 indicates that the developed model fits the data well. Moreover, we analyzed the residuals to detect any potential discrepancies that may not be detected by the R^2 [70]. A good model should

16 SWMLR: Stepwise Multilinear Regression.

17 Y_w: Wheat productivity.

18 a: The intercept of Y_w axis.

19 β: Regression coefficient.

20 e: Random error that denotes the residual.

21 O_i: Observed wheat productivity (Mg ha^{-1}).

22 P_i: Predicted wheat productivity by model (Mg ha^{-1}).

23 R^2: Coefficient of determination.

show a random distribution of its standardized residuals against the fitted values with no clear pattern around the zero value.

3. Results and discussion

3.1. Changing trend in climate-related variables

Statistically significant trend models for the tested climate-related parameters are illustrated in Fig. 2, and their related statistical indices

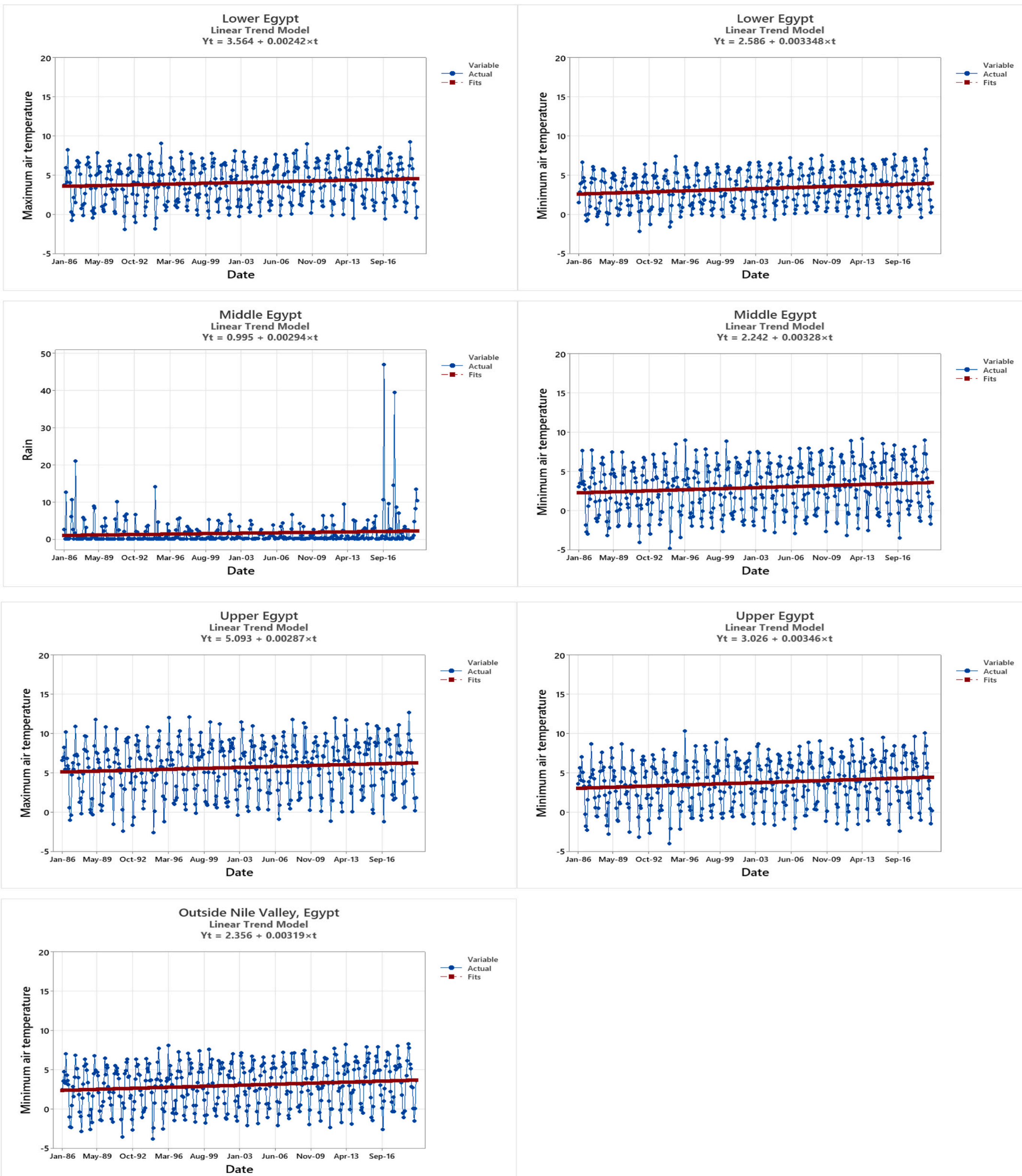

Fig. 2. Illustration for the statistically significant trend models for the tested climate parameters in each study zone in Egypt.

are summarized in Table 1. The accumulated monthly rainfall in middle Egypt varied from a minimum of 0.0 mm to a maximum of 50.44 mm during the last three decades. This study zone exhibits a significant positive z-value of 4.571 with a MAD value of 1.98. It implies a significant increasing trend in rainfall in this area. The obtained S_s value of 0.0007 estimated the increased quantity of the total rainfall in middle Egypt by 0.28 mm from 1987 to 2019, with a decadal rate of 0.08 mm. The other study zones did not show any significant change in rainfall trend.

The observed increasing trend of P in middle Egypt contrasts with the report by the World Bank Group [6], which stated that rainfall decreased by ~22 % in the past 30-years. This discrepancy might be attributed to the aggregation of Egypt as a single study zone in their report, which could have masked the small increasing trend in middle Egypt. Moreover, the distinction between extreme P events (flash floods) that they considered in their report, which increased in frequency during the same period, might have also influenced their results. The current study did not differentiate between extreme P events' values and other P registrations, which might have contributed to our observation. Yet, both results imply that rainfall is not a reliable water source in Egypt and highlight the critical situation that the country faces currently and in the future regarding water availability and related issues under business-*as*-usual scenario.

In addition, the study detected a significant warming trend in Egypt's climate. Table 1 displays positive z-values for the registered air temperatures in all study zones that signify a notable trend. The T_{min} rose significantly at higher rates than the T_{max} in both lower and upper Egypt from 1986 to 2019. The registered T_{max} values increased significantly by 0.24 °C and 0.35 °C per decade (MAD of 2.00 and 2.74) in lower and upper Egypt, respectively during the study period. Meanwhile, T_{min} increased significantly in all study zones, at a rate of 0.40 °C, 0.41 °C, 0.42 °C, and 0.43 °C per decade (MAD of 2.37, 2.61, 1.89, and 2.51) in the outside Nile valley of Egypt zone, middle Egypt, lower Egypt, and upper Egypt, respectively during 1987–2019.

The obtained results corroborate the findings of Ngarukiyimana et al. [71], who documented a higher increasing rates in T_{min} than in T_{max} across certain locations in Rwanda during 1961–2014. Confirmative evidence is provided by an additional study [72], which recorded a tripling in the rate of increase of T_{min} relative to T_{max} during the period from 1951 to 1990 across various terrestrial regions worldwide. In addition, these findings are consistent as well with the World Bank Group's analysis of historical (1901–2019) and future (2020–2100) climate variables in Egypt, using the Coupled Model Inter-comparison Project No.5 (CMIP5) projections under the RCP 2.6 that reflects very strong mitigation actions and RCP 8.5 that assumes business-*as*-usual scenario [6]. They reported that average air temperature increased in Egypt by 0.53 °C per decade during the past thirty years compared to 0.1 °C per decade during 1901–2013. They also projected an increase in average temperature in Egypt by 1.5 °C–3.0 °C during 2040–2059 under the RCP 8.5 scenario, suggesting that the country will become hotter and drier in the future.

3.2. Changing trend in crop-related variables

3.2.1. Change in growing degree days

The observed significant trend models for the accumulated GDD in each study zone in Egypt are presented in Fig. 3. The accumulated wheat GDD exhibited a significant upward trend (positive z-values in Table 1) in all study zones.

The accumulated wheat GDD had the lowest average (1815) outside the Nile valley of Egypt, followed by middle Egypt (1886), then lower Egypt (1943), and upper Egypt (2494). Generally, optimum average wheat GDD in Egypt ranges between 1583 and 1665 [17,33]. The obtained S_s values in Table 1 indicated that GDD increased the highest in middle Egypt ($S_s = 9.25$), followed by upper Egypt ($S_s = 8.735$), then the outside zone of the Nile valley of Egypt ($S_s = 8.448$), and lower Egypt ($S_s = 7.757$). This indicated a significant increase in wheat GDD during the period 1987–2019 by 92.50, 87.35, 84.48, and 77.57 GDD per decade in middle and upper Egypt, outside the Nile valley, and lower Egypt, respectively.

However, the observed significant increasing trend of GDD is not favorable for long-season wheat varieties. Wheat requires ~125–160 GDD for emergence, 44–48 GDD for leaf development, 200–213 GDD for tillering, 223–238 GDD for stem elongation, 215–242 GDD for anthesis, 261–273 GDD for seed filling, 366–382 GDD for dough stage, and 104–109 GDD for maturity complete [33]. Therefore, the higher the accumulated GDD, the shorter the period that the wheat will need to reach maturity [73,74]. Since the observed average GDD in upper Egypt was 829 GDD higher than the optimum rates reported by Refs. [17,33], short-season wheat varieties in this zone might be a good option for mitigating climate impact on wheat productivity.

Table 1
Significantly developed trend models for the studied parameters in each study zone and their associated statistics.

zone	Variable	Trend Model	N	min.	max.	mean	st.dv	z-value	Sen's slope	MAD
Lower Egypt	T_{max}	$Y_t = 3.564 + 0.00242\,t$	408	15.05	31.14	23.59	4.54	2.32*	0.0020	2.00
	T_{min}	$Y_t = 2.586 + 0.003348\,t$	408	11.39	26.35	18.67	4.29	2.52**	0.0035	1.89
	GDD	$Y_t = 1834.2 + 6.38\,t$	33	1688	2177	1943	121	3.24	7.7570	98.5
	Y_w	$Y_t = 5.12 + 0.06017\,t$	33	4.83	7.00	6.14	0.68	5.53**	0.0586	0.29
Middle Egypt	P	$Y_t = 0.995 + 0.00294\,t$	408	0.0	50.44	2.05	4.84	4.571**	0.0007	1.98
	T_{min}	$Y_t = 2.242 + 0.00328\,t$	408	4.35	24.74	14.73	5.76	2.50*	0.0034	2.61
	GDD	$Y_t = 1757.4 + 7.59\,t$	33	1552	2191	1886	147	2.99*	9.2500	95.6
	ET_c	$Y_t = 1.689 + 0.00177\,t$	230	1.16	6.91	2.71	1.51	1.98*	0.0020	1.18
	Y_w	$Y_t = 5.197 + 0.06053\,t$	33	4.88	7.05	6.23	0.70	5.40**	0.0614	0.31
Upper Egypt	T_{min}	$Y_t = 3.026 + 0.00346\,t$	408	8.22	28.14	19.08	5.48	2.75*	0.0036	2.51
	T_{max}	$Y_t = 5.093 + 0.00287\,t$	408	19.32	40.59	31.45	6.04	2.10*	0.0029	2.74
	GDD	$Y_t = 2307.5 + 7.5\,t$	33	2165	2773	2494	147	3.02	8.7350	100.20
	ET_c	$Y_t = 2.034 + 0.002\,t$	230	1.48	6.78	3.11	1.52	2.36*	0.0020	1.20
	Y_w	$Y_t = 4.914 + 0.0571\,t$	33	4.62	6.76	5.89	0.69	5.10**	0.0561	0.33
Outside Nile valley Egypt	T_{min}	$Y_t = 2.356 + 0.00319\,t$	408	6.19	24.93	15.80	5.26	2.77*	0.0033	2.37
	GDD	$Y_t = 1661.3 + 7.11\,t$	33	1511	2089	1815	136	3.08	8.4480	89.50
	ET_c	$Y_t = 1.329 + 0.00185\,t$	230	0.96	5.40	2.17	1.17	2.46*	0.0010	0.91
	Y_w	$Y_t = 4.044 + 0.05583\,t$	33	3.90	6.28	4.99	0.63	5.72**	0.0604	0.25

*Statistically significant at $p \leq 0.05$ and ** statistically significant at $p \leq 0.001$.
N: number of the tested variable observations, min: minimum value, max: maximum value, st.dv.: standard deviation, MAD: mean absolute deviation, T_{min}: minimum air temperature (°C), T_{max}: maximum air temperature (°C), GDD: accumulated growing degree days, P: accumulated rainfall (mm month^{-1}), ET_c: crop evapotranspiration (mm day^{-1}), and Y_w is wheat productivity (Mg ha^{-1}).

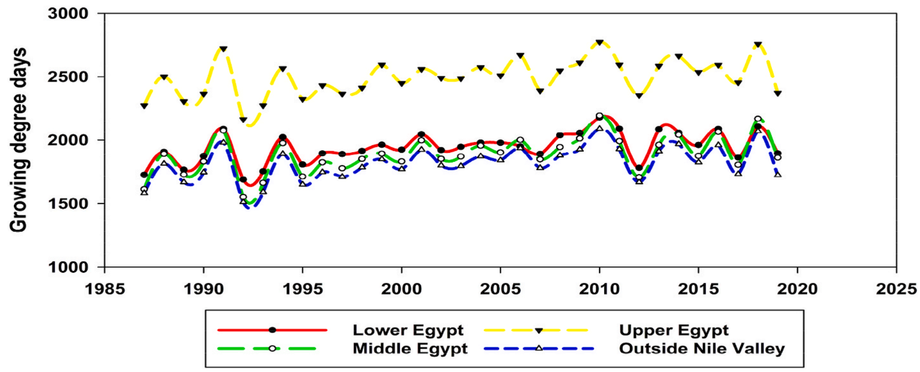

Fig. 3. Illustration for the statistically significant trend models for the observed accumulated growing degree days during wheat crop season for the period 1986–2019 in each study zone in Egypt.

3.3. Evapotranspiration and crop water requirements

A non-significant increase in ET_o is detected in all study zones ($P \geq 0.05$). Table 2 indicates the percentage of observed increase in ET_o for each month of the cropping season from November to mid-April during 2009–2019 compared to 1987–1997.

The ET_c of wheat increased significantly in middle Egypt, upper Egypt, and outside the Nile valley areas, while lower Egypt did not show any significant change in the same period. Fig. 4 shows the significant increasing trend in ET_c for each area. The results showed that ET_c increased by 0.02 mm per decade ($S_s = 0.002$ and MAD = 1.2) in middle and upper Egypt, and by 0.01 mm per decade ($S_s = 0.001$ and MAD = 0.9) in the area outside the Nile valley in Egypt during 1987–2019. The observed increase in ET matched the observed increase in air temperatures in the last three decades (Fig. 2). The results acquired are in alignment with the findings of Caretta et al. [7], who observed a 0.5 mm increment in ET attributable to the elevated air temperatures recorded between 1980 and 2010. This is corroborated by the research of Tan et al. [75], which investigated the determinants impacting ET_c through remote sensing-based techniques in the North China Plain noting a substantial correlation between ET_c and rising air temperatures.

The observed increase in ET_o and ET_c from 1987 to 2019 exacerbates the already critical issue of water scarcity for agricultural demands, particularly in arid zones such as Egypt. Research conducted by Padrón et al. [76] has identified the augmentation of evapotranspiration as a primary contributor to the diminution of water resources, surpassing the effects of reduced precipitation. Furthermore, they have posited that an amplification in evapotranspiration could diminish plant water availability, thereby elevating the risk of agricultural failure due to drought conditions [77]. In alignment with these findings, the World Bank Group [6] has acknowledged that increased temperatures may aggravate the tension between water requirements for agriculture and domestic consumption, among other uses, by further elevating evapotranspiration levels. Data from Tables 1 and 2 illustrate that the surge in evapotranspiration has led to a rise in CWR by ~12 % in Lower Egypt, ~15 % in Middle and Upper Egypt, and ~18 % in outside the Nile valley zone of Egypt in 2009–2019 compared to 1987–1997, presuming 100 % irrigation efficiency and the absence of salinity leaching necessities. These observations are corroborated by the work of Abd Elwahab [78], who noted a mean increase of 9 % in wheat CWR in Egypt, based on his analysis of the impact of climatic change on wheat and its water requirements, utilizing climatic data from 2014 to 2018 relative to the interval of 1984–1988. The observed increment in CWR has been attributed to the rise in evapotranspiration. These results are consistent with the outcomes reported by Liu et al. [79] in their investigation of the Heihe River basin in China, and by Mostafa et al. [80] in their study in middle Egypt zone, both of which indicate a detrimental effect of climatic change on wheat CWR under various projected climatic scenarios.

Table 2
The percentage of observed increase ($P \geq 0.05$) in reference evapotranspiration during wheat cropping season (from November to mid-April) in each study zone in Egypt in 2009–2019 compared to 1987–1997.

Month	Lower Egypt	Middle Egypt	Upper Egypt	Outside the Nile valley of Egypt
November	9	15	15	16
December	11	18	16	19
January	13	17	18	22
February	21	23	21	27
March	15	16	17	21
April	1	4	2	6

3.4. Wheat productivity: climate and policy impact

Fig. 5 illustrates the observed increasing trend in wheat productivity from 1987 to 2019 in all study zones in Egypt. The zone outside the Nile valley of Egypt had relatively lower wheat productivity (4.99 Mg ha^{-1}) than other areas during the same period. The highest average in wheat productivity was observed in middle Egypt (6.23 Mg ha^{-1}), followed by lower Egypt (6.14 Mg ha^{-1}), and upper Egypt (5.89 Mg ha^{-1}). The observed increasing wheat productivity over the last three decades in Egypt was mainly thanks to the applied wheat self-sufficiency plans and strategies, the adoption of high-yielding wheat varieties, and providing subsidies and free machinery to encourage the farmers to expand the wheat-cultivated lands [81].

Egypt is actively pursuing strategies to enhance its wheat self-sufficiency, aiming to boost it from 47 % in 2021 to 70 % by the year 2030 [19]. In the past two decades, the country has encouraged the cultivation of new varieties of wheat that are resistant to drought and salinity, alongside enhancing farm management techniques, aiming to achieve a yield of 8.5 Mg ha^{-1} by the year 2030 [82]. The main events and strategies that affected wheat productivity in Egypt during the last two decades were summarized by Abdalla et al. [81] and presented in Figure S3 of the supplement material.

The observed low average wheat productivity outside the Nile valley zone of Egypt was mainly due to it being a newly reclaimed region, which practically was desert area [6]. It resulted in more differences in wheat productivity from one location to another varying from an average minimum of 3.90 Mg ha^{-1} to an average maximum of 6.28 Mg ha^{-1} during 1987–2019 (Table 1), depending on the applied on-farm management practices. Although the observed lower average of wheat productivity outside the Nile valley zone of Egypt from 1987 to 2019, it came the second place in the wheat productivity increasing rates (0.60 Mg ha^{-1} per decade) after middle Egypt, which comes in first place (0.61 Mg ha^{-1} per decade). Therefore, wheat productivity outside the Nile valley might increase over the next few decades if sustainable on-farm management plans are adopted and upscaled.

On the other hand, the increasing rate of wheat productivity in lower

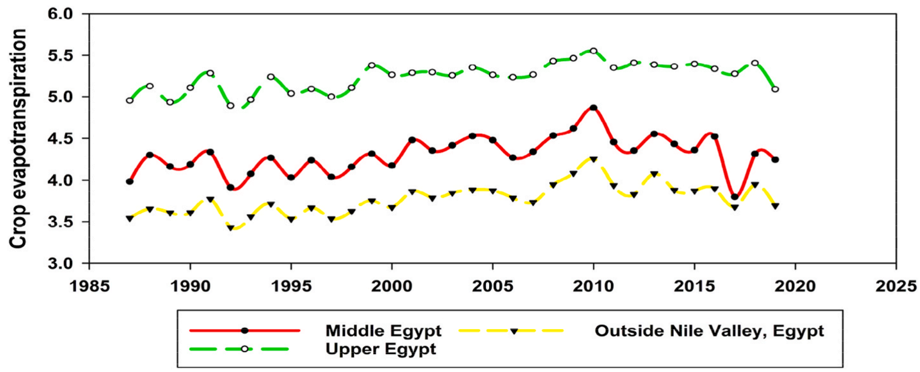

Fig. 4. Illustration for the statistically significant trend models for the observed crop evapotranspiration during 1987–2019 in each study zone in Egypt.

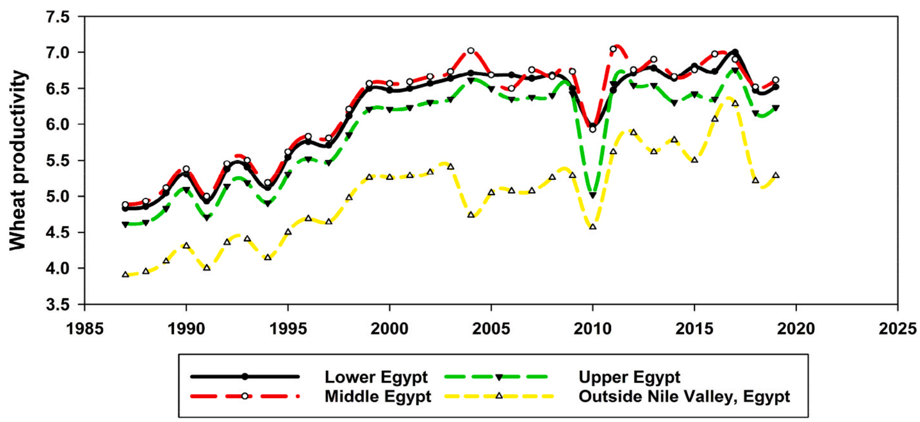

Fig. 5. Illustration for the statistically significant trend for the observed wheat productivity during 1987–2019 in each study zone in Egypt.

and upper Egypt was 0.59 and 0.56 Mg ha^{-1} per decade, respectively. This might be due to the observed significant increase in T_{max} in lower and upper Egypt (Table 1).

The supplementary materials documented residual plots for all the developed models with significant relationships at $P \leq 0.05$ based on the SWMLR analysis in Figure S2. Only the significant models that showed no clear pattern of the standardized residuals versus the fitted values indicating high performance of the developed model [70] are presented in Table 3 and Fig. 6, respectively. The unstandardized coefficients were used for each equation due to their insensitivity to the scale changes [83].

The relationship between the tested year-to-year climate variables with significant impact on the year-to-year wheat productivity during 1987–2019 in every study zone in Egypt is illustrated in Fig. 7. Results revealed that although the observed increase in wheat productivity during the last three decades, climate variables were not a good contributor to this improvement. The year-to-year wheat productivity in Egypt was negatively affected by the year-to-year fluctuations in the climate variables (T_{max}, T_{min}, and GDD). Wheat productivity in lower Egypt was inversely related to the annual GDD and T_{max} (Fig. 7). Middle Egypt was not significantly affected by the observed changing trends in P, T_{min}, T_{max}, and GDD. Wheat productivity in lower Egypt was significantly associated with the changes in T_{max} and T_{min} during February and April, respectively.

Generally, wheat crop needs about 20–35 days for the emergence and floral initiation, 45–60 days for terminal spikelet, 60–80 days to the first node, 90–120 days for the heading stage, 100–130 days for the anthesis stage, and 140–170 days for the maturity and physiological stages [67,68]. Therefore, the obtained results indicated that the node stage (during February) was the most vulnerable stage to the changes in T_{max}, while the anthesis and physiological stages (during April) were extremely sensitive to the changes in T_{min} in lower Egypt during 1987–2019. On the other hand, the anthesis and physiological stages in the upper Egypt zone and the floral initiation stage (during December)

Table 3
Significantly developed models' Statistics by stepwise multilinear regression analysis. Dependent variable is year-to-year wheat productivity.

Zone	Target period	Model**	R^2	Independent variables	Unstandardized coefficient**	
					β	Standard error
Lower Egypt	Season*	$y = 0.003 \bullet GDD - 0.609 \bullet T_{max}$	0.32	GDD*	0.003	0.001
				T_{max}	−0.609	0.202
	Feb.*	$y = -0.065 \bullet T_{max}$	0.13	T_{max}	−0.065	0.030
	Apr.*	$-0.124 \bullet T_{min}$	0.20	T_{min}	−0.124	0.045
Upper Egypt	Apr.*	$y = -0.092 \bullet T_{max}$	0.15	T_{max}	−0.092	0.040
Outside Nile valley, Egypt	Season**	$-0.001 \bullet GDD$	0.26	GDD	−0.001	0.000
	Dec.*	$y = -0.086 \bullet T_{max}$	0.18	T_{max}	−0.086	0.034

Where T_{min} is the year-to-year minimum air temperature in °C, T_{max} is the year-to-year maximum air temperature in °C, GDD is the year-to-year accumulated growing degree days in °C and P is year-to-year accumulated rainfall in mm. * model is statistically significant at P < 0.05.

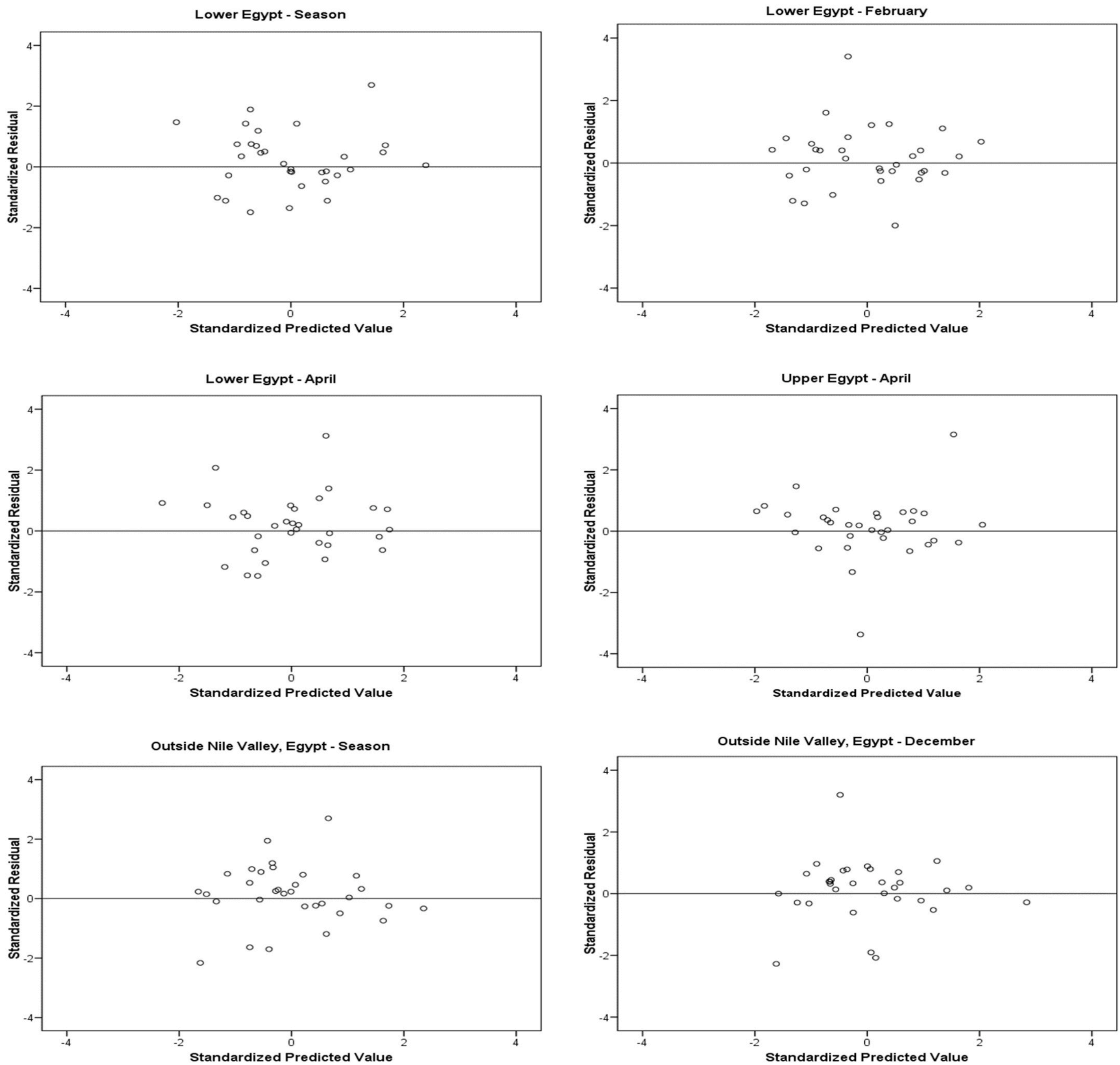

Fig. 6. Residual plots for the SWMLR significant models at P ≤ 0.05 illustrating the distribution of standardized residuals against the fitted values in all study zones in Egypt.

outside the Nile valley of Egypt zone were the most affected development stages by the changes in T_{max}.

This agrees with Abdalla et al. [81], who reported that the improvement in wheat productivity from 2001 to 2010 in Egypt was mainly driven by the adoption of modern technologies, improved wheat varieties, and other measures to achieve the goals of Egypt's self-sufficiency plans for wheat production. They also warned that ignoring climate change impacts, among other factors including fungal diseases and rising input prices, might hinder wheat productivity in Egypt and obstruct its self-sufficiency strategic plans. They reported a decrease in wheat productivity in Egypt by 16 % in 2010 than in 2009 due to a severe drought and heat wave event that affected the crops that year [81]. In addition, Aslam et al. [30] found in their study that increasing air temperature above 30 °C has a significant negative impact on wheat biomass and grain yield. On the other hand, wheat productivity experienced a noticeable decline in all study zones in Egypt in 2010 (Fig. 5). Therefore, the observed negative relationship between climate variables and wheat productivity in Egypt (Fig. 7) rings the bell to consider them in the country's self-sufficiency plans for wheat. Despite the adopted strategies to increase wheat productivity during the last three decades, an extreme heat wave and drought event resulted in dropping productivity by ~16 % in 2010 [81].

4. Conclusions and recommendations

Egypt tended to be warmer with significant increase in air temperatures during the past three decades. However, minimum air temperature was increasing at higher rates than maximum air temperatures in all Egypt. Rainfall remained unreliable water source in all study zones in Egypt despite the observed extremely low increasing trend in middle

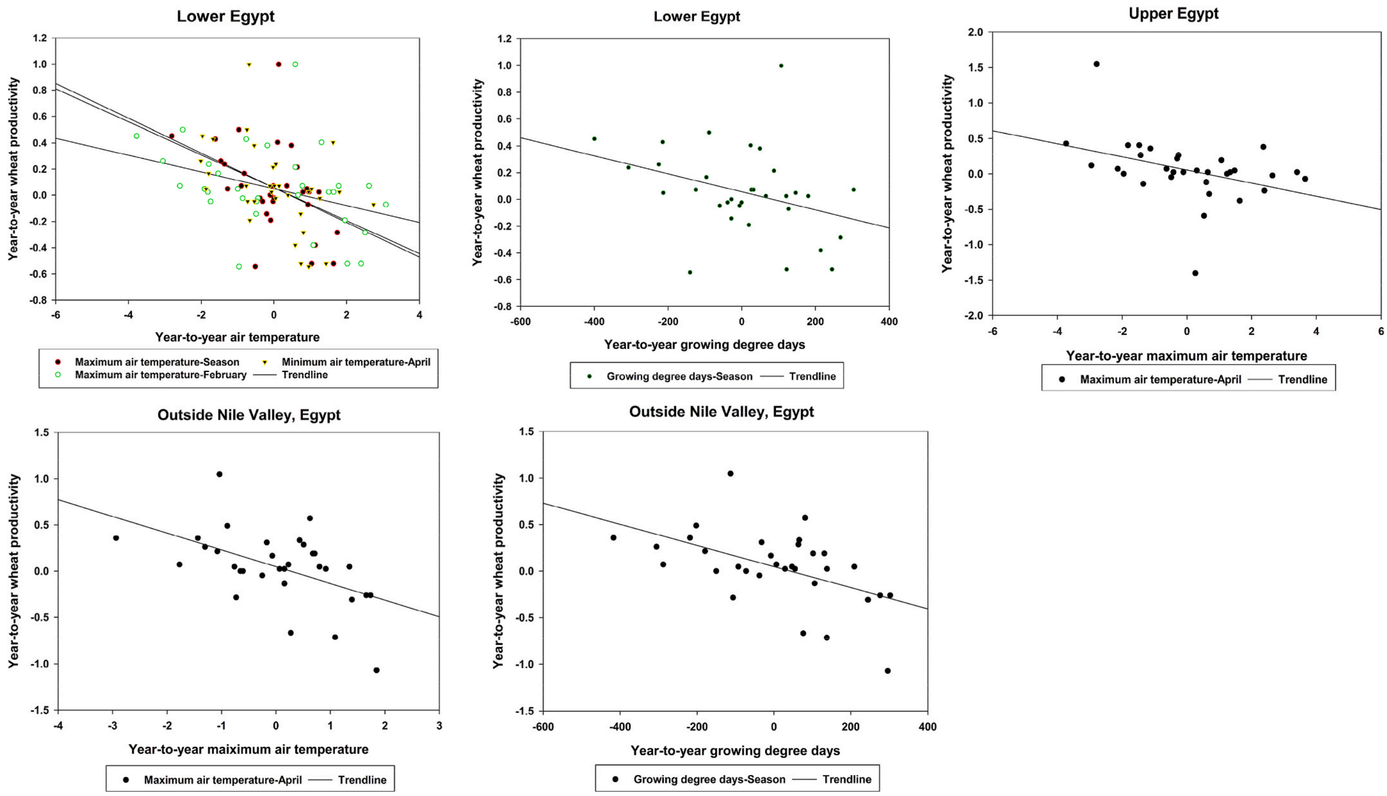

Fig. 7. Relationship between the tested year-to-year climate variables with significant impact on year-to-year wheat productivity during 1987–2019 in the selected study zones in Egypt.

Egypt. Crop water requirements in all study zones were increased in response to the observed significant increase in evapotranspiration rates. Despite the successful adopted self-sufficiency plans for increasing wheat productivity in Egypt during 1987–2019, still climate change is an essential parameter that should be considered in these strategies since it negatively affects wheat productivity and crop water requirements, the main two pillars for wheat production under limited water resources conditions. In lower Egypt, wheat node stage was the most sensitive stage to maximum air temperature while the anthesis and physiological stages were the most vulnerable wheat development stages to minimum air temperatures. However, the floral initiation stage was the most sensitive stage to changes in maximum air temperature in the outside the Nile valley zone in Egypt.

Considering these circumstances, careful and wise management planning should be encouraged for more sustainable wheat self-sufficiency strategies in Egypt and zones that share the same climate change circumstances. Therefore, it is recommended to.

1 Boost the cultivation of short-season heat, drought, and disease-tolerant wheat varieties and adopt the best management practices for wheat cultivation, especially in upper Egypt to mitigate the negative impact of climate change and to benefit the high growing degree days values and reduce crop water demand.
2 Endorse wheat intensification in middle Egypt since it was the least affected zone by changes in climate parameters and impact on wheat productivity during 1987–2019.
3 Promote wheat cultivation in the outside Nile valley zone in Egypt as it is a promising new reclaimed area for horizontal and vertical expansion of wheat crop since it had the highest increasing rates in wheat productivity during 1987–2019.
4 Encourage and upscale the application of treated nonconventional water in the agricultural sector to cope with the limited water sources and the observed increase in crop water demands.

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CRediT authorship contribution statement

Rania Gamal: Writing – original draft, Validation, Resources, Investigation, Conceptualization. **Ayman Farid Abou-Hadid:** Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Mohie El Din Omar:** Resources. **Maha Elbana:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2024.101181.

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