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Population prediction of whiteflies (*Bemisia tabaci*) in changing environments of Egypt

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ABSTRACT

Climate change is expected to have an impact on pest management in different agroecosystems. Pest management strategies in these agroecosystems may need to be adjusted in responses to long term changes in pest populations. The whitefly *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) is an important pest on a global scale because of its voracious feeding and its role in transmission of numerous plant viruses in many agroecosystems. A field study was conducted to help elucidate the impact of climate change on populations of whiteflies in vegetable agroecosystems in Egypt. Mild winter temperatures allow whiteflies to live year-round in these agroecosystems. Predictions of populations of B. tabaci were done for agroecosystems in three Egyptian governorates (Dakahlia, Damietta, and Sohag). The Sohag site was in the Nile Valley (about 520 km south of Cairo). The other two sites (Dakahlia and Damietta) were in the Nile River Delta (about 110 km and 155 km north of Cairo, respectively). Historical seasonal patterns as well as long-term values (for the years 2041 and 2070) of populations of whiteflies were estimated. The results based on our analysis of the temperature and whitefly population patterns spanning an excess of three decades (from 1980 to 2013) support that the temperature continued to rise, and the whitefly population continued to increase among years in each agroecosystem. Results from this research will help agricultural stakeholders in understanding the impact of changing environments on populations of whiteflies.

Keywords: *Bemisia tabaci*, pest population, population model, vegetable, climate change, sweetpotato whitefly, Egypt.

RESUME

Prévision de la population d'aleurodes (*Bemisia tabaci*) dans les environnements changeants de l'Égypte

Les changements climatiques sont supposés avoir un impact dans la lutte antiparasitaire des ravageurs dans différents agroécosystèmes. La strategie de lutte antiparasitaire dans ces agroécosystèmes pourrait être ajustée en function des changements à long terme de la population des ravageurs. L'aleurode *Bemisia tabaci* (Gennadius) (Hemiptère: Aleyrodidae) est un important ravageur d'envergure globale due à sa voracité alimentaire et son role dans la transmission de nombreux virus de plantes dans plusieurs agroécosystèmes. Une étude de terrain a été menée pour aider à élucider l'impact du changement climatique sur les densités de populations d'aleurodes dans les agroécosystèmes légumineux de l'Egypte. Les températures douces de l'hiver permettent aux aleurodes de maintenir leurs populations tout le long de l'année dans ces écosystèmes. Les prédictions des densités de populations de *B. tabaci* ont été faites pour les agroécosystèmes localisés dans trois gouvernorats égyptiens (Dakahlia, Damietta, and Sohag). Le site Sohag était sitiué dans la vallée du Nil (à environ 520 km au sud de Caire). Les deux autres sites (Dakahlia and Damietta) étaient dans le delta du Nil (110 km et 155 km au nord de Caire, respectivement). Les tendances saisonnières historiques de même que les données à long terme (pour les années 2041 et 2070) ont été estimées. Les résultats basés sur notre analyse des modèles de températures et les tendances des densités de populations d'aleurodes couvrant trois décennies (de 1980 à 2013) soutiennent que la température a continué de monter, et les populations d'aleurodes ont aussi continué à s'accroitre au cours des années dans chaque agroécosystème. Les résultats de cette étude vont aider les acteurs agricoles à une meilleure compréhension de l'impact des changements environnementaux sur les densités de populations d'aleurodes.

Mots-clés : *Bemisia tabaci*, population du ravageur, modèle de population, végétale, changement climatique, aleurode à la patate douce, Egypte.

INTRODUCTION

The management of whiteflies, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) complex, is a global challenge in various agroecosystems. These insects feed on plants and transmit plant viruses in both open and protected environments, thereby severely damaging crops in small, medium, and large cropping systems. Moreover, environmental horticulture plants are attacked and damaged by this insect (Olaniyi et al., 2021). This invasive pest has long demonstrated that it is very adaptive to components in the changing environment such as pesticides (Dângelo et al., 2018; Perring et al., 2018). Eggs are primarily deposited on the lower surface of leaves where the nymphs remain sessile (except early phase of the first instar) during their feeding and development; high populations can rise quickly with adults emerging within about three weeks following oviposition in warm climates (Simmons and Mahroof, 2011; Perring et al., 2018). As a result of the whitefly pressure, growers commonly use insecticides to try to manage the whiteflies and associated diseases in their crops (Perring et al., 2018). Therefore, its control is particularly challenging in many agroecosystems. Whiteflies in the *B. tabaci* complex are known to feed on over 1,000 species of plants (Simmons et al., 2008; Abd-Rabou and Simmons, 2010), transmit over 100 plant viruses (Jones, 2003), and are spread across every continent, except Antarctica (De Barro et al., 2000a; De Barro et al., 2000b). In addition to crop plants, other primary plant species that serve as hosts for whiteflies include weeds and other plants in the agroecosystem that have no or reduced economic value. However, all of these host plants facilitate the buildup of local and regional whitefly populations, eventually affecting many economically important plants. Moreover, *B. tabaci* and its role as a plant vector has elevated its threat to food security (Kalyebi et al., 2018). Therefore, it is critical to understand whitefly population dynamics for the development of effective control strategies for this pest.

The changing environment usually alters the population dynamics of insect species (Fahrner and Aukema, 2018), including whiteflies. Specifically, the life cycle of whiteflies can vary greatly depending on abiotic factors such as temperature and relative humidity (Enkegaard, 1993; Simmons and Elsey, 1995; Drost et al., 1998; Simmons and Mahroof, 2011; Curnutte et al., 2014). Changes in insects, plants, and their relationships are expected to occur with continued warming of the earth, even though organisms are generally not adapted to dramatic changes in temperatures and CO_2 (Porter et al., 1991; Zvereva and Kozlov, 2006; Legaspi et al., 2011). The current trend of enhanced atmospheric CO_2 is associated with increased surface temperatures, and the monthly CO_2 level reached a record average of 421 ppm in May 2022 (National Oceanic and Atmospheric Administration, 2022) after having exceeded the record of 400 ppm in May 2014 for the first time in the modern era (National Oceanic and Atmospheric Administration, 2020). Temperature is the primary abiotic factor that affects whitefly populations (Naranjo et al., 2010; Curnutte et al., 2014), presumably because of the fitness alteration of *B. tabaci* due to the temperature change (Curnutte et al., 2014).

Multiple studies support that there are at least 40 morphologically indistinguishable cryptic species in the *B. tabaci* complex that can only be distinguished by molecular analyses (De Barro et al., 2011; Liu et al., 2012; Firdaus et al., 2013; Hu et al., 2017). Among them, the Middle East Asia Minor 1 (MEAM1) species of the *B. tabaci* complex is the most widespread globally and destructive whitefly that attacks plants (Stansly and Naranjo, 2010; Rosen et al., 2015). Two members of the *B. tabaci* species complex, the MEAM1 population and the Mediterranean (MED) population (Dinsdale et al., 2010) attack crops in fields in Egypt (Abd-Rabou, 1999). Mild winters appear to facilitate the establishment of whitefly population expansion during the warmer seasons (Simmons and Elsey, 1995; Curnutte et al., 2014; Olaniyi et al., 2021). This indicates the important role of seasonal population variations in the persistence of whiteflies. The main objective of this study is to predict population changes of the whitefly *B. tabaci* in response to environmental changes, namely from increasing temperatures, in selected agroecosystems in Egypt. In this research, we focused on modeling the response of whitefly populations to high and low temperatures over time.

MATERIALS AND METHODS

Study site and data collection

A field study was set up to predict populations of *B. tabaci* under climate change scenarios in selected agroecosystems in Egypt. Specifically, we selected the nearest meteorological stations for the field sites in three Egyptian governorates (Dakahlia, Damietta, and Sohag). The Sohag site was at an Agricultural Research Center experiment station near the city of Girga, while the Dakahlia and Damietta sites were on private vegetable farms near the town of Aga and city of El Zarqa, respectively. Dakahlia and Damietta are adjacent governorates that are located in the Nile Delta, near the Mediterranean Sea (the sites were about 110 km and 155 km, respectively, north of Cairo), while Sohag is located in Central Egypt in the Nile Valley (the site was about 520 km south of Cairo). Maximum and minimum temperature data were obtained for each of four sets of growing seasons spanning over three decades (1980, 1990, 2012, and 2013).

The temperature data were collected for each site starting in mid-October of each year (1980, 1990, 2012, and 2013) until mid-January of each following year, covering a span of four months for each sample season. A 1,200 m^2 plot of squash, *Cucurbita pepo* L., was established at each study site. At each of the study sites, weekly counts of *B. tabaci* nymphs were taken from leaves of 30 random squash plants per location during each sample period. Most nymphs were found on the abaxial leaf surface, but counts were combined for nymphs on both leaf surfaces. Although the data were based on *B. tabaci* for all years, we note that the identity of specific cryptic species was not confirmed by DNA analyses of the nymphs. The major surrounding crop at the southern site (Sohag) was corn (*Zea mays*, a poor host for *B. tabaci*; Simmons et al., 2008) and some okra (*Abelmoschus esculentus*) were grown. Conversely, the northern sites (Dakahlia and Damietta) consisted of assorted species of vegetable crops in the landscape including squash, tomato, and beans. This is a predictive study.

Data analyses

Data analyses were conducted using SAS v. 9.4 (SAS Institute, 2013), except where otherwise noted. Data from the whitefly counts for each field site were integrated with the meteorological data. Daily high temperature data per location per season were averaged across each set of seven days per location and per year to correspond with the weekly whitefly counts (Table 1). Regression analyses were conducted on average temperature per week and on weekly whitefly count per location by year with whitefly count as a dependent variable and temperature as an independent variable. A paired t-test was used to compare population collected for the 2013 season (mid-October 2013 to January 2014) and population predicted for 2041 season, and compare population collected for the 2013 season and population predicted for 2070 season. Based on the projected monthly changes in temperature according to a Representative Concentration Pathways (RCP; Intergovernmental Panel on Climate Change 2019a) 4.5 and RCP 8.5, the projected late season whitefly populations were estimated using regression formulas:

$N = 2.12 * T^2 + 15.36 * T - 437.65$ for the Sohag site,
$N = 20.01 * T^2 – 650.33 * T + 6028.54$ for the Damietta site, and
$y = 2.20439x^2 + 62.345x – 949.64$ for the Dakahlia site for the years 2013, 2041, and 2070.

Where, N represents the counts of whiteflies and T represents temperature. These formulas were developed from the regression of whitefly counts on temperature for 2013 for a given site and selected from the best fit regressions from the 2013 data as later described herein. The baseline counts from 2013 were used to compare with estimated populations for 2041 and 2070 per site.

Modeling seasonal temperature profile

Annual environmental temperature variation was estimated for the three aforementioned locations based on selected historical data. Following Vaidya and Wang (2020), the time dependent profile of the environmental temperature was described by the following sinusoidal periodic function with the period of 52 weeks (1 year):

$$T(t) = A \sin\left(\frac{2\pi}{52}t + B\right) + C,$$

where A is the amplitude, B is the phase shift, and C is the mean temperature. First, weekly high and low temperature data were averaged to obtain weekly temperature in each location. To these weekly average temperature data form October 24 to January 21, the sinusoidal function given above was fitted to estimate the value of amplitude (A), shift (B) and the mean temperature (C) for each location and each year considered. Using the estimated corresponding values of A, B, and C, the temperature for the remaining weeks of the year were predicted for each year considered (1980, 1990, 2012, and 2013) and for each of the locations (Dakahlia, Damietta, and Sohag).

To identify the relationship between temperature and whitefly population, we perform regression analysis on the data collected with nymph counts as the response variable and temperature as the predictor variable. For this analysis, 14-week data of average temperature and experimental whitefly nymph counts were used. For each year and each location, both linear and quadratic regression models were considered, and the best models (Table 2) were chosen on the basis of their AIC (Akaike information criterion) values (Hastie et al., 2009; James et al., 2017).

Sensitivity of population to amplitude and mean value of temperature

To assess the effects of amplitude and mean temperature on the whitefly nymph count, a large number of temperature profiles were generated using the temperature profile model for varying amplitude and mean value in the intervals $[A-10, A+10]$ and $[C-10, C+10]$, respectively. For the generated temperature profiles, the best models identified corresponding to year and location were used to predict whitefly populations.

RESULTS

Temperature variation

As presented in Table 3, we observe that among the three locations, the mean temperature and the amplitude are similar between Dakahlia and Damietta, whereas Sohag experienced the greater fluctuation in mean temperature and amplitude. These findings are complementary to the actual data presented in Table 1.

Model identification and population pattern

The best regression models for each year and each location are presented in Table 2. Models for all locations and years are statistically significant, and the R^2 values ranged from 81%-97% (Table 2). We observe that the quadratic regression model best describes the experimental temperature and nymph data for the Damietta (Table 2). For the other two locations, a mix of linear and quadratic regression model are the best models.

The best model identified for each year and location and the estimated temperature profile were used to predict the nymph counts throughout the year (Figure 1). For the first 14 weeks, the model describes well the experimental data for the nymph population over (Figure 1). We found that the lowest weekly average number of nymphs for the Sohag location occurred around the third week of January (about the 12th week in the plot) in all years considered.

Table 1. Mean maximum and mean minimum daily temperatures per site in three governorates in Egypt during the late growing season (from mid-October to mid-January)

Location	Year 1980	Year 1990	Year 2012	Year 2013
	Mean maximum daily temperature (ºC)			
Dakahlia	21.3 ± 1.0	22.5 ±1.1	23.4 ±1.2	24.5 ±1.1
Damietta	19.9 ±1.0	21.3 ±0.9	22.6 ±0.9	23.0 ±1.1
Sohag	22.5 ±1.2	23.5 ±1.4	25.3 ±1.2	26.0 ±1.3
	Mean minimum daily temperature (ºC)			
Dakahlia	11.5 ±0.8	12.8 ±1.0	14.0 ±1.0	14.5 ±1.0
Damietta	14.2 ±1.0	14.7 ±1.1	15.7 ±1.1	16.9 ±0.9
Sohag	8.1 ±1.0	9.3 ±1.1	10.1 ±1.0	10.6 ±1.1

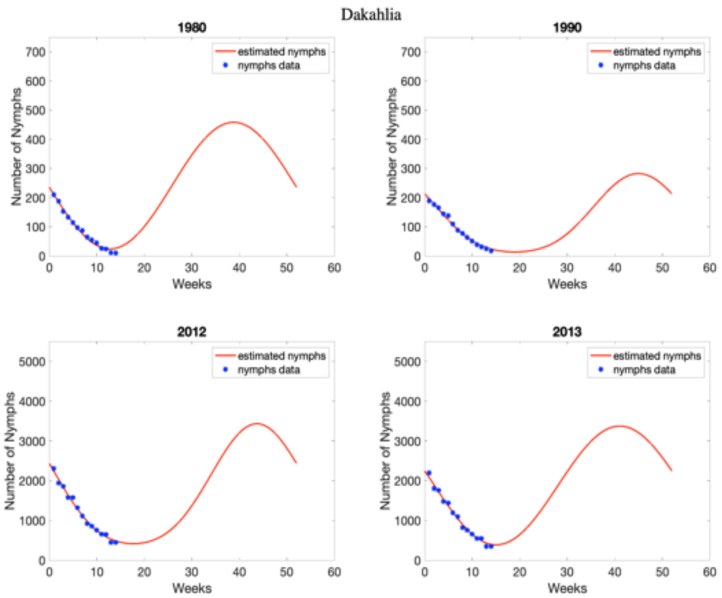
Table 2. The regression models that best fit the temperature and whitefly nymph count data in three different locations (Dakahlia, Damietta, and Sohag governorates in Egypt) for each year considered (1980, 1990, 2012, 2013). T is the temperature and N is the counts for whitefly counts

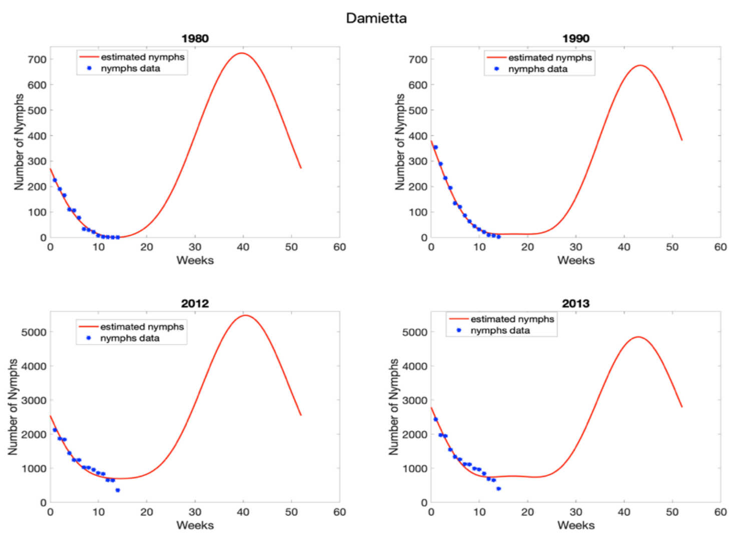
Year	Dakahlia	Damietta	Sohag
1980	$N = 18.96 * T - 223.69$	$N = 1.02 * T^2 - 16.14 * T + 35.25$	$N = 10.52 * T - 118.85$
1990	$N = 0.68 * T^2 - 8.60 * T + 26.59$	$N = 2.9 * T^2 - 76.54 * T + 518.35$	$N = 0.74 * T^2 - 14.14 * T + 71.32$
2012	$N = 5.40 * T^2 - 60.40 * T + 335.431$	$N = 9.82 * T^2 - 255.6 * T + 2324.57$	$N = 93.38 * T - 1121.44$
2013	$N = 144.85 * T - 1751.99$	$N = 20.01 * T^2 - 650.33 * T + 6028.54$	$N = 2.12 * T^2 + 15.36 * T - 437.65$

Table 3. The value of amplitude (A), phase shift (B) and mean temperature (C) in three different regions (Dakahlia, Damietta, and Sohag) for four different years (1980, 1990, 2012, and 2013)

Year	Dakahlia			Damietta			Sohag		
1980	A = 11.44,	B = 3.16,	C = 24.52	A = 10.91,	B = 3.1,	C = 24.14	A = 18.04,	B = 3.41,	C = 30
1990	A = 7.9,	B = 2.42,	C = 18.94	A = 7.75,	B = 2.62,	C = 20.58	A = 11.64,	B = 2.89,	C = 22.68
2012	A = 8.87,	B = 2.57,	C = 21.3	A = 10.1,	B = 2.96,	C = 25.1	A = 15.92,	B = 3.3,	C = 30
2013	A = 10.3,	B = 2.9,	C = 25.1	A = 7.76,	B = 2.67,	C = 22.82	A = 15.8,	B = 3.23,	C = 30

For the other two locations, the dates for the lowest weekly average of nymph count varied by year. For example, for the Dakahlia location, the lowest weekly average nymph count occurred in about the third week of January in the years of 1980 and 2013, while it occurred around the third week of March in the years 1990 and 2012. Similarly, the highest weekly average number of nymphs in Sohag is observed around the 3rd week of July (about 38th week in the plot) and for the other two locations, the highest weekly average number of nymphs in Dakahlia and Damietta are around the 1st week of August (about 41st week in the plot).





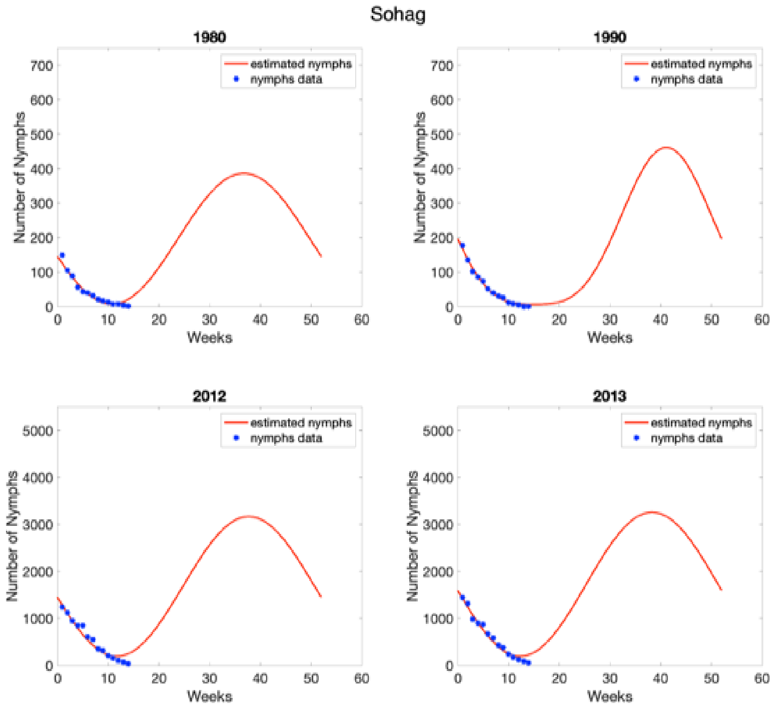


Figure 1. Experimental data for whitefly nymph counts for 14 weeks (blue dots) and the model prediction for throughout the years of 1980, 1990, 2012, and 2013 in locations in governorates (Dakahlia, Damietta, and Sohag) in Egypt

Population prediction with respect to amplitude and temperature

The corresponding population prediction for the three locations are presented in Figure 2. Our estimates of the nymph population for various amplitudes and temperatures show that the increase in the amplitude and average temperature increase the nymph population of whiteflies in all three locations. For example, at the Dakahlia site (Figure 2), when the average temperature is 31 and amplitude is 16, the predicted nymph population is 4,243, while the population at the same location increases to 5,691 when the amplitude and average temperatures are 18.3 and 33, respectively. At the Damietta location, which has a higher average temperature and amplitude compared to other two locations, the number of nymphs reaches 14,620 and 21,670, respectively.

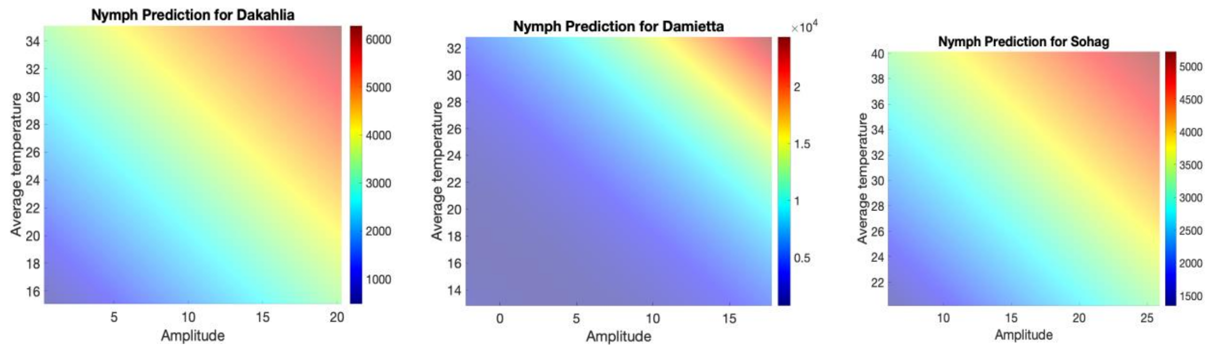


Figure 2. Prediction of whitefly nymph population over a range of amplitude and average temperature at locations in three governorates (Dakahlia, Damietta, and Sohag) in Egypt

Long term population estimation

In this section, we present the prediction of the long-term whitefly population for the years 2041 and 2070), and compare them with the 2013 population. Projected temperature increases at RCP 4.5 ranged from 0-1.3°C per month for the locations while temperatures at RCP 8.5 ranged from 0.5-2.0°C. Whitefly population counts are predicted to be higher at the Dakahlia and Damietta locations compared to Sohag. Although there is a significant increase in the RCP 8.5 projected whitefly population for the Dakahlia ($P < 0.05$) and the Sohag ($P < 0.01$) sites, the other seasonal population projections are not significantly different from the 2013 population (Figure 3). Overall whitefly counts are projected to vary based on month of the year (Figure 3).

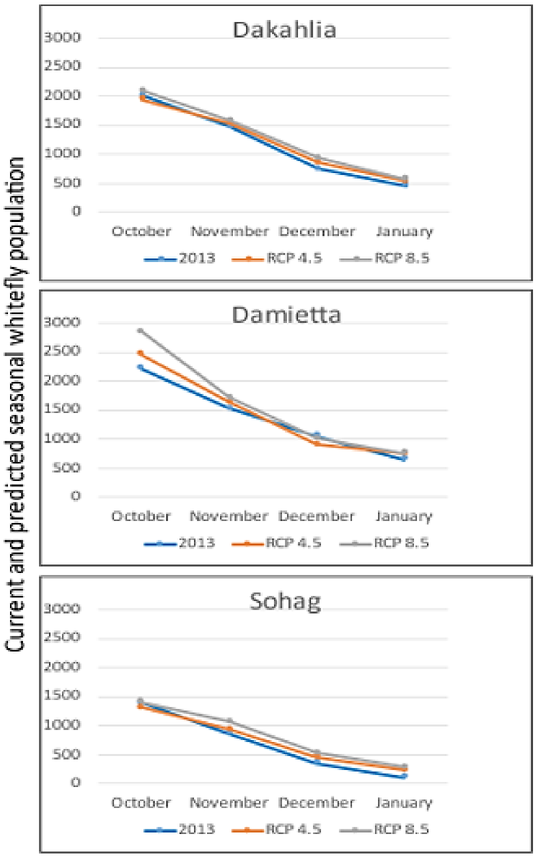


Figure 3. Current and long-term predicted whitefly (*B. tabaci*) populations (nymphs) per 30 leaves of squash plants in the field in three governorates (Dakahlia, Damietta, Sohag) in Egypt during the late growing season (mid-October to mid-January). RCP = Representative Concentration Pathways.

DISCUSSION

Our study supports that a gradual increase in temperature in Egypt may result in an elevated population of *B. tabaci* over time. Based on our analysis of the temperature and whitefly population patterns spanning in excess of three decades (from 1980 to 2013), we predict that the temperature continued to rise, and the whitefly population trended to increase among years during the late growing season (mid-October to mid-January). Among the three locations, temperature was similar between the Dakahlia and Damietta sites which had experienced the lower average daily fluctuations (Tables 1, 3) and may have been moderated by their closeness to the Mediterranean Sea.

Conversely, Sohag experienced the greater temperature fluctuation. This great fluctuation may be because Sohag is in a region with lower relative humidity as compared with the two former sites (unpublished data). A limitation of our study is that the models do not incorporate meteorology data other than temperature. We acknowledge that low relative humidity can have a negative affect on whitefly populations (Simmons & Mahroof, 2011). On the other hand, an environment that has high relative humidity may be more conducive to the establishment and epizootic of entomopathogenic fungi which can suppress populations of whiteflies (Osborne and Landa, 1992; Wu et al., 2020). However, humidity data are not available for the experimental sites in our study. Rainfall is another meteorological factor which can affect populations of whiteflies (Katono et al., 2021). The frequency and duration of rainfall events can decrease populations of whiteflies in crops as a result of physical injury to the whiteflies from raindrops. Some degree of protection from rain events is provided to the whiteflies because of their behavior to primarily congregate on the lower leaf surface. Yet decisions and actions of humans can affect the populations of insects not only directly, such as from employing management strategies, but also indirectly.

For example, any adjustment in anthropogenic activities in response to increasing temperatures may further affect insect populations in the future. Crop producers are encouraged to seek crop production practices that result that provide economic benefit with the least cost. For example, increasing temperatures may result in growers increasing the use of overhead irrigation. Overhead irrigation can reduce whitefly populations (Castle et al., 1996; Abd-Rabou and Simmons, 2012), and the additional irrigation may have a subtractive impact on whitefly populations. We further recognize that although the changing climate has resulted in more common conditions of hot days, hot nights, and heat waves (Intergovernmental Panel on Climate Change, 2019b), the data used in the development of our models are not sensitive to temperature trends beyond 2013.

Populations of *B. tabaci* can be explosive from a single mated adult female on a good host plant under favorable temperatures. Therefore, growers commonly observe no or a few whiteflies followed by high populations within just a few weeks. The overall higher populations of whiteflies at the Dakahlia and Damietta sites for each year considered in our study (Figure 1) may have been affected by multiple factors, including increased abundance of wild and cultivated host plants in these regions. Long-term global changes may result in a matrix of abiotic and biotic factors that may affect the abundance and distribution of insects in a given agroecosystem (Luquet et al., 2019). However, our results indicate that temperature is the primary factor affecting whitefly populations in Egypt. This is consistent with previous studies (Naranjo et al., 2010; Curnutte et al., 2014).

Whitefly populations that are present during the cooler time of the year may have an impact on the population dynamics during the following warmer time of the year. The elevated population of whiteflies during the late season may have a potential positive effect on providing a bridge to increased whitefly abundance during the early growing season, in comparison with populations from early growing seasons of previous years. Although corresponding data were not collected after the whitefly population decreased in January, during the cooler time of the year, we suspect that any factors that may enhance the population of the whiteflies from the previous season may result in an increase during the spring as compared with populations from the previous spring seasons. The population models in Figure 1 lend support for this scenario. Mild winters can be survived in low populations of *B. tabaci* on wild and cultivated plants and their population can re-establish in the subsequent warmer season (Simmons & Elsey, 1995). Another important factor in whitefly population dynamics is the availability of suitable host plants to bridge from one season to another (Olaniyi et al., 2021).

At each site in our study, different species of host plants (weeds and crops) were available to interact with the whitefly population on squash, but data were not recorded from the other plant species. Because corn is a poor host for *B. tabaci* (Simmons et al., 2008) and because it was the major crop in the landscape in the southern site, we suspect that movement of whiteflies in and out of the experimental crop may have been restrained. However, we suspect that there may have been more movement by whiteflies among the vegetable crops at the two northern sites. In a laboratory study with a range of temperatures to which *B. tabaci* populations were adapted, Curnutte et al. (2014) reported that 28ºC was most favorable for the fitness of *B. tabaci*. Those data were based on whitefly populations reared at constant temperatures whereas field temperatures generally fluctuate during each day. The average daily temperature during each month of the warmest year (2013) of the study herein ranged from a mean high of 25.2ºC at the Dakahlia site during the last half of October to a mean low of 14.3ºC at the Sohag site during the first half of January (Table 1).

Within a given agroecosystem, there are numerous considerations which may guide insect pest management decisions. Among these are the economic value of the crops, the cost to control the pests of interest, the population of the pests, and the impact of pest management on the agroecosystem. For whitefly pests, chemical control is a common management tool even though there are numerous adverse effects on using many conventional insecticides (Castle et al., 2009; Horowitz et al., 2020; Sparks et. al., 2020). Off-targets of the strategy of using treatments with conventional pesticides include natural enemies in the agroecosystem (Cole et al., 2010; Abd-Rabou & Simmons, 2015).

Conventional pesticides in conduction with changing environments may directly and indirectly affect the population dynamics of natural enemies in an agroecosystem. Numerous species of natural enemies have been reported to attack *B. tabaci* in Egypt (Abd-Rabou and Simmons, 2014). Any influence that the climate may have on natural enemies may result in a direct impact on their ability to help mitigate populations of *B. tabaci*. Moreover, it is unknown how proficient the natural enemies of *B. tabaci* would be in a scenario of a modest increase in temperature. We suspect that there would be varying responses among the different species of natural enemies, notably in cases of generalist natural enemies which in term may be impacted by the other organisms in the agroecosystem. The role of biological components in the agroecosystems needs future research consideration. Results from this study will help in the understanding of the impact of changing environments on the population of whiteflies in vegetable production systems where this pest lives year-round.

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Conflicts of interest

The authors declare no conflict of interest.

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