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*Original article (Orijinal araştırma)*

# Modeling the distribution of the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann, 1824) (Diptera, Tephritidae) in Turkey and its range expansion in Black Sea Region[1]

Akdeniz meyve sineği, *Ceratitis capitata* (Wiedemann, 1824) (Diptera, Tephritidae)' nin Türkiye'deki dağılımının modellenmesi ve yayılış alanında Karadeniz Bölgesi'ndeki genişleme

**Tayfun KAYA[2] Eren ADA[3] Kahraman İPEKDAL[4*]**

## Summary

Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann, 1824) (Diptera, Tephritidae), an important fruit pest, is not expected to expand its range under current climatic conditions with an exception of the Black Sea coasts that was hypothesized to be suitable for *C. capitata* invasion. After finding a *C. capitata*-infested mandarin in western Black Sea Region of Turkey, we tested this hypothesis. We first used ecological niche modeling approach to determine suitable places for *C. capitata* survival in Turkey; and then visited eastern Black Sea region of Turkey where the model predicted to be suitable. For the model, we collected fruit samples from 49 localities in southern and western Turkey, where *C. capitata* presence has already been known, and one locality from northern Turkey, where its presence has not been known, in November 2014 and 2015 and transferred them to laboratory to observe adult emergence. *Ceratitis capitata* adults emerged from 44 localities. These localities were used as the presence data for the model. After obtaining the model results, we visited eastern Black Sea Region, and collected fruit samples from 11 different localities, and transferred them to laboratory to observe adult emergence. In total, 49 *C. capitata* adults emerged. Thus, presence of *C. capitata* was shown in the eastern Black Sea for the first time. The model also predicted that suitable areas in the Black Sea basin for *C. capitata* survival tend to expand in future.

**Keywords:** Mediterranean fruit fly, *Ceratitis capitata*, ecological niche modeling, Eastern Black Sea, range expansion

## Özet

Önemli bir meyve zararlısı olan Akdeniz meyve sineği, *Ceratitis capitata* (Wiedemann, 1824) (Diptera, Tephritidae)'nın yayılış alanını mevcut iklimsel koşullar altında genişletmeyeceği düşünülmekte; ancak, *C. capitata* istilası için uygun görünen Karadeniz kıyılarının bu genellemenin dışında olduğu varsayılmaktadır. Batı Karadeniz Bölgesi'nde *C. capitata* ile enfekte olmuş bir mandalina bulunduktan sonra bu varsayım sınanmıştır. Öncelikle Türkiye'de *C. capitata*'nın yaşamasına uygun olan alanların tespiti için ekolojik niş modellemesi yaklaşımı kullanılmış, daha sonra da modelin uygun olarak tahmin ettiği Doğu Karadeniz Bölgesi'nde arazi çalışmaları yapılmıştır. Modelleme için *C. capitata*'nın varlığı bilinen Akdeniz ve Ege Bölgesi'nden 49 noktadan ve *C. capitata*'nın varlığı bilinmeyen Karadeniz Bölgesi'nden bir noktadan 2014 ve 2015 yılları Kasım ayında meyve örneği toplanmış ve laboratuvara getirilerek ergin çıkışları izlenmiştir. Toplamda 44 farklı yöreden ergin *C. capitata* elde edilmiştir. Bu noktalar model için veri olarak kullanılmıştır. Modelleme sonuçlarına göre Karadeniz Bölgesi'nde arazi çalışmaları gerçekleştirilmiştir. Meyve örnekleri 11 noktadan toplanarak laboratuvara getirilmiş ve ergin çıkışları izlenmiştir. Bu örneklerden toplam 49 ergin *C. capitata* çıkmıştır. Böylece Doğu Karadeniz'de Akdeniz meyve sineğinin ilk kez varlığı gösterilmiştir. Model ayrıca gelecekte Karadeniz havzasında *C. capitata* için uygun olan alanların oluşacağını da göstermektedir.

**Anahtar sözcükler:** Akdeniz meyve sineği, *Ceratitis capitata*, ekolojik niş modellemesi, Doğu Karadeniz, yayılış alanı genişlemesi

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[1] This study was supported by TÜBİTAK - KBAG (Project No: 114Z667).
[2] Ahi Evran University, Faculty of Engineering and Architecture, Department of Environmental Engineering, Bağbaşı Campus, 40100 Kırsehir, Turkey
[3] Hacettepe University, Faculty of Science Department of Biology, Beytepe, 06800 Ankara, Turkey
[4] Ahi Evran University, Faculty of Science and Literature, Department of Biology, Bağbaşı Campus, 40100 Kırsehir, Turkey
* Corresponding author (Sorumlu yazar) e-mail: kipekdal@gmail.com
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## Introduction

Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Tephritidae), is a cosmopolitan species distributed in the Middle East, southern Europe, Africa, South America and Australia (Liquido et al., 1990; Bergsten et al., 1999; USDA, 2003; Bayrak & Hayat, 2012). Its host range consists more than 400 plant species, including several economically valuable fruits. This fact along with its capacity for long-distance flight makes *C. capitata* one of the most important fruit pests in many countries worldwide (Liquido et al., 1990; Harris & Olalquiaga, 1991; Bergsten et al., 1999; Israely et al., 2005; Meats & Smallridge, 2007).

*Ceratitis capitata* adult females generally prefer mature fruit with thin skin for oviposition. Citrus fruits except lemon, kiwi and persimmon are among the highly effected hosts of *C. capitata*. Banana, eggplant, grape, tomato, papaya, and pepper are among its other important hosts with relatively high damage. However, *C. capitata* was also found to attack cacti, cucumber and zucchini in the laboratory and almond, bean and pineapple in the field, but the economic level of damage in these hosts is unknown (Elekçioğlu, 2013; UF-IFAS, 2016). Economically important plants that have been reported being attacked in Turkey by *C. capitata* are citrus except apple, avocado, fig, lemon, peach, persimmon, pomegranate, and quince (Elekçioğlu, 2009, 2013).

Damage caused by *C. capitata* occurs immediately after eggs are laid in fruit or soft tissues of the host plant, and emerging larvae start feeding. Moreover, saprophytic bacteria transmitted during oviposition cause fruit to decay (Bergsten et al., 1999). Bacterial activity leads to color deterioration in fruit which starts from the point of oviposition and expands to the entire fruit over time; and eventually the fruit turns yellow and falls off earlier (Elekçioğlu, 2013). *Ceratitis capitata* has been included in the EPPO A2 quarantine list (EPPO, 1981) because of the damage it causes to fruit.

Turkey is a major fruit-producing country (e.g. annual production of citrus, peach, pomegranate, and fig is about 3,976, 650, 450 and 300 kt, respectively) (TUIK, 2016). *Ceratitis capitata* is one of the most important insect pests of fruit in Turkey (Hendrichs et al., 1995; Elekçioğlu, 2009). Due to its quarantine status, it can also cause issues in fruit export (Elekçioğlu, 2009).

According to the Turkish Ministry of Agriculture, *C. capitata* is mainly present along the southern and western coast areas of Turkey (Kaya, 2013 and references cited therein). EPPO (2015) claims that considering seasonal and geographic conditions that *C. capitata* needs to survive, it has reached the limits of its possible range, and expansion of its range is not expected with an exception of the Black Sea basin. Thus, the potential invasion of the Black Sea basin by *C. capitata* rests as a hypothesis to test. A recent article in local newspapers reported that *C. capitata* was present in Samsun (central Black Sea Region), therefore this hypothesis needs to be seriously considered. In a previous field trip to Bartın in the western Black Sea Region of Turkey in 2015, we found *C. capitata* larvae in mandarin which further strengthened the need to test this hypothesis.

Ecological niche modeling (ENM) is widely used to predict the potential geographic distribution of species using presence data and environmental variables (Guisan & Thuiller, 2005). Based on the assumptions of species–climate equilibrium and stability of ecological niches through time (Nogués-Bravo, 2009), ENM can also be used to predict past or future geographic distribution of species (Peterson et al., 2002; Hijmans & Graham, 2006; Waltari et al., 2007; Waltari & Guralnick, 2009; Gür, 2013). These projections can be useful in planning conservation and pest management programs (Sen et al., 2016).

In this study, we tested the hypothesis described above through a region wide survey. For this purpose, (1) we determined localities where *C. capitata* can survive in Turkey by modeling its ecological niches, and (2) we conducted field work along the Black Sea coastal line in Turkey. We also built ENM-based future distribution maps which can be useful in planning pest management strategies.

## Materials and Methods

To use as the species presence data, we collected fruit samples from 49 localities in southern and western Turkey where the occurrence of *C. capitata* was already known and from one locality (Bartın) in the Black Sea Region where no presence data has been reported before this study (Table 1, Figure 1). Collection of fruit samples were carried out in November 2014 and 2015.

Table 1. *Ceratitis capitata* (Wiedemann, 1824) presence data collected in Turkey to use in ecological niche modeling

| | Coordinates / Altitude (m) | Locality | Host Fruit |
|---|---|---|---|
| 1 | 39° 31' N, 26° 30' E / 5 | Behram, Çanakkale | mandarin |
| 2 | 39° 34' N, 27° 00' E / 9 | Edremit, Balıkesir | mandarin |
| 3 | 39° 12' N, 26° 47' E / 10 | Altınova, Balıkesir | orange |
| 4 | 39° 05' N, 26° 54' E / 20 | Dikili, İzmir | mandarin |
| 5 | 38° 51' N, 27° 02' E / 10 | Yenişakran, İzmir | mandarin |
| 6 | 38° 37' N, 27° 08' E / 23 | Emiralem, İzmir | mandarin |
| 7 | 38° 27' N, 27° 14' E / 63 | Bornova, İzmir | mandarin |
| 8 | 38° 09' N, 27° 22' E / 32 | Torbalı, İzmir | mandarin |
| 9 | 38° 14' N, 27° 58' E / 138 | Ödemiş, İzmir | mandarin, orange |
| 10 | 37° 57' N, 27° 23' E / 17 | Selçuk, İzmir | mandarin |
| 11 | 37° 48' N, 28° 27' E / 200 | Aydın | mandarin |
| 12 | 37° 43' N, 27° 17' E / 62 | Kuşadası, Aydın | mandarin, orange |
| 13 | 37° 48' N, 27° 17' E / 26 | Kuşadası-Söke, Aydın | mandarin |
| 14 | 37° 54' N, 28° 19' E / 75 | Nazilli, Aydın | mandarin |
| 15 | 37° 46' N, 27° 37' E / 28 | Söke-Koçarlı, Aydın | mandarin |
| 16 | 37° 41' N, 27° 59' E / 70 | Çine, Aydın | mandarin |
| 17 | 37° 34' N, 27° 49' E / 85 | Karpuzlu, Aydın | mandarin |
| 18 | 37° 20' N, 27° 47' E / 15 | Milas, Muğla | mandarin |
| 19 | 37° 19' N, 27° 46' E / 78 | Milas, Muğla | mandarin, orange |
| 20 | 37° 03' N, 28° 21' E / 10 | Marmaris, Muğla | mandarin |
| 21 | 36° 58' N, 28° 41' E / 28 | Köyceğiz, Muğla | mandarin |
| 22 | 37° 00' N, 28° 30' E / 83 | Marmaris-Köyceğiz, Muğla | mandarin, orange |
| 23 | 36° 47' N, 28° 50' E / 2 | Muğla-Fethiye, Muğla | orange |
| 24 | 36° 38' N, 29° 18' E / 177 | Fethiye, Muğla | mandarin, orange |
| 25 | 36° 19' N, 29° 19' E / 6 | Kınık, Antalya | mandarin, orange |
| 26 | 36° 12' N, 29° 38' E / 2 | Kaş, Antalya | orange |
| 27 | 36° 14' N, 30° 01' E / 10 | Demre, Antalya | mandarin, orange |
| 28 | 36° 19' N, 30° 11' E / 2 | Finike, Antalya | mandarin, orange |
| 29 | 36° 21' N, 30° 17' E / 3 | Kumluca, Antalya | mandarin, orange |
| 30 | 36° 24' N, 30° 28' E / 5 | Çıralı, Antalya | fig |
| 31 | 36° 35' N, 30° 32' E / 22 | Kemer, Antalya | mandarin |
| 32 | 36° 59' N, 30° 36' E / 292 | Döşemealtı, Antalya | mandarin |

Table 1. (Continued)

| | Coordinates / Altitude (m) | Locality | Host Fruit |
|---|---|---|---|
| 33 | 36° 49' N, 31° 22' E / 60 | Manavgat, Antalya | mandarin |
| 34 | 36° 33' N, 32° 03' E / 20 | Alanya, Antalya | mandarin |
| 35 | 36° 09' N, 33° 40' E / 10 | Silifke, Mersin | fig |
| 36 | 36° 33' N, 34° 09' E / 505 | Çamlıgöz, Mersin | fig, mandarin, orange |
| 37 | 36° 37' N, 34° 20' E / 2 | Alata, Mersin | fig, mandarin, orange |
| 38 | 36° 51' N, 34° 34' E / 281 | Aslanköy, Mersin | fig, mandarin, orange |
| 39 | 36° 52' N, 34° 35' E / 281 | Bulluklu, Mersin | mandarin |
| 40 | 36° 54' N, 34° 49' E / 93 | Bağlarbaşı, Mersin | fig, mandarin, orange |
| 41 | 36° 55' N, 34° 54' E / 14 | Tarsus, Mersin | fig, mandarin, orange |
| 42 | 36° 59' N, 35° 02' E / 39 | Yenice, Mersin | fig, mandarin, orange |
| 43 | 37° 00' N, 35° 20' E / 33 | Adana | mandarin, orange |
| 44 | 36° 55' N, 35° 20' E / 21 | Havutlu, Adana | mandarin, orange |
| 45 | 36° 50' N, 36° 11' E / 29 | Dörtyol-Erzin, Hatay | mandarin, orange |
| 46 | 36° 35' N, 36° 10' E / 8 | İskenderun, Hatay | fig, mandarin, orange |
| 47 | 36° 12' N, 36° 07' E / 131 | Çekmece, Hatay | fig, mandarin, orange |
| 48 | 36° 07' N, 36° 00' E / 85 | Mızraklı, Hatay | fig, mandarin, orange |
| 49 | 36° 06' N, 35° 56' E / 17 | Samandağ, Hatay | fig, mandarin, orange |
| 50 | 41° 38' N, 32° 12' E / 249 | Güzelcehisar, Bartın | mandarin |

Fruit samples were collected either directly from trees or among the fallen fruit on the ground around the trees visited. Samples were transferred to the laboratory in 750ml glass jars with covers having a net with a mesh size 0.5mm fixed on a ventilation hole with a diameter of 2.5mm. In the laboratory, fruit samples were transferred separately to 1.5 l plastic pupation boxes with covers having a net with a mesh size 0.5mm fixed on a ventilation hole with a diameter of 50mm. The fruit samples were placed on sterilized sand poured in the pupation box to the height of 20mm. These boxes were checked daily for 20d in order to observe larvae jumping out of the decaying fruit to pupate in the sand. After 20d, pupae in the sand were collected using a sieve and transferred to Petri dishes for rearing. Adult emergence from the pupae were checked and recorded daily. Emerging adults were identified under a dissection microscope. Only the localities from infested fruit were collected were used as presence data for the ENM.

We mostly collected presence data from the western and southern Turkey. In order to correct this sampling bias, a Gaussian kernel density of presence records was created by a sampling bias distance of two decimal degree (Elith et al., 2010; Fourcade et al., 2014).

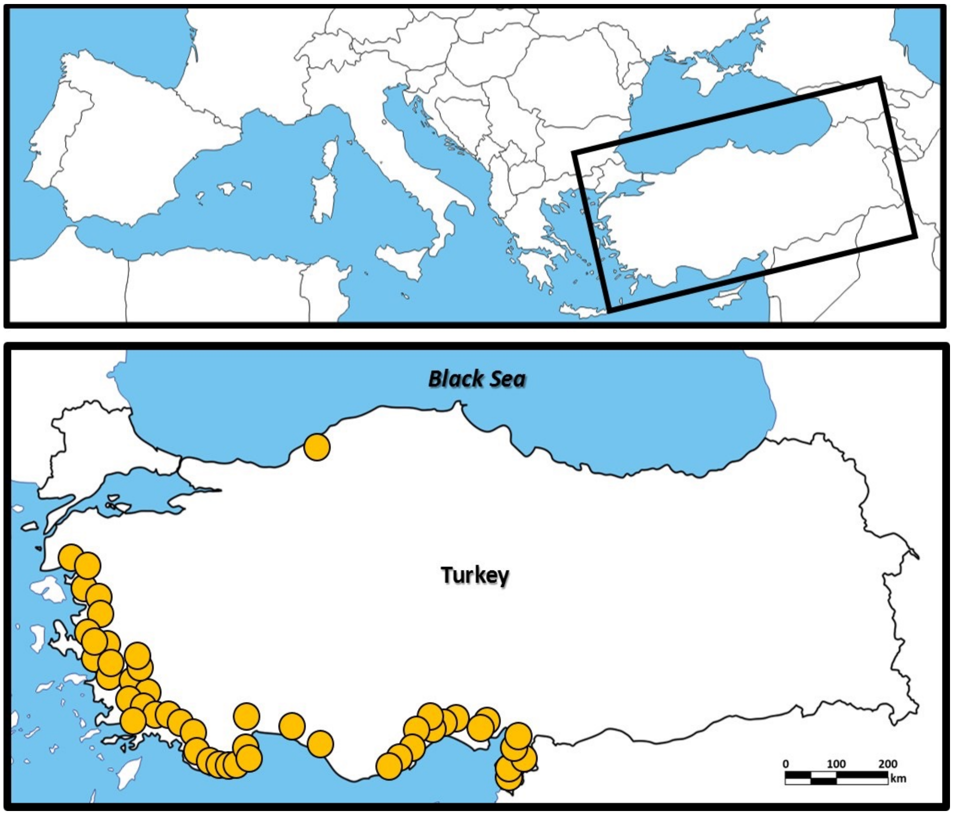


Figure 1. Distribution of the presence data for the Mediterranean fruit fly in Turkey used in ecological niche modeling.

Current (1950 to 2000) and projected future (2050 and 2070) bioclimatic variables (BIO1-19) were downloaded from the WorldClim database (Hijmans et al., 2005) at a resolution of 2.5 arc min. The 2050 bioclimatic data was the average for 2041 to 2060 and the 2070 data was the average for 2061 to 2080. Both future bioclimatic variables are based on the CCSM4 general circulation model simulation (see Coupled Model Intercomparison Project Phase 5; cmip-pcmdi.llnl.gov/cmip5). Future bioclimatic variables are available in four different representative concentration pathways (RCPs) at WorldClim which are rcp26, rcp45, rcp60 and rcp85 (Moss et al., 2008). In this study, we used bioclimatic variables that were adopted by rcp60 scenario only. The variables were masked by following coordinates: 34$^o$ to 43$^o$ N and 24$^o$ to 47$^o$ E. All of 19 bioclimatic variables were used for modeling.

To predict the potential distribution of *C. capitata* in Turkey under current and projected future bioclimatic conditions, we used the maximum entropy machine learning algorithm in the software MAXENT 3.3.3k (Phillips et al., 2006). All GIS operations were conducted using the software SDMtoolbox 1.1c (Brown, 2014) implemented in the ArcGIS version 10.2.2. MAXENT was run with default settings. Modeling was performed with ten-fold cross-validation runs. 80% of the presence records were used to train the modeling and 20% were used to test it for each run. For future projections, the modeling was repeated for the 2050 and 2070 data sets separately.

The area under curve (AUC) was used to evaluate the model performance (Fielding & Bell, 1997). An AUC > 0.5 indicates that the model performs better than a random prediction (i.e. AUC ≥ 0.9 = very good, 0.9 > AUC ≥ 0.8 = good, and AUC < 0.8 = poor) (Gassó et al., 2012). The model outputs were generated in logistic format.

After obtaining the results from the ENM study described above, we visited the localities along the Black Sea coastal line where the model expected relatively higher probability of *C. capitata* occurrence. We collected fruit samples from 11 localities in November 2014 and 2015, and transferred them to laboratory (Table 2, Figure 2). Details related to field and laboratory procedures were as described above.

Table 2. Fruit sampling localities visited to search *Ceratitis capitata* (Wiedemann, 1824) presence along the Black Sea Region of Turkey

| | Coordinates / Altitude (m) | Locality | Host Fruit |
|---|---|---|---|
| 1 | 41° 14' N, 36° 15' E / 200 | İlkadım, Samsun | apple, mandarin, medlar, pear, pomegranate |
| 2 | 41° 12’ N, 36° 57’ E / 9 | Terme, Samsun | apple, pear, persimmon, quince |
| 3 | 41° 03’ N, 37° 28’ E / 15 | Fatsa, Ordu | apple, orange, persimmon |
| 4 | 41° 03’ N, 37° 46’ E / 10 | Perşembe, Ordu | apple , mandarin, pear, persimmon |
| 5 | 41° 01’ N, 38° 56’ E / 200 | Görele, Giresun | mandarin |
| 6 | 40° 56’ N, 38° 42’ E /13 | Espiye, Giresun | apple, medlar, persimmon |
| 7 | 40° 56’ N, 38° 14’ E / 10 | Bulancak, Giresun | apple, mandarin, persimmon |
| 8 | 41° 02’ N, 39° 13’ E / 40 | Beşikdüzü, Trabzon | apple |
| 9 | 41° 01’ N, 29° 33’ E / 55 | Akçaabat, Trabzon | mandarin |
| 10 | 41° 10’ N, 40° 53’ E / 28 | Pazar, Rize | mandarin |
| 11 | 41° 04’ N, 41° 01’ E / 350 | Çamlıhemşin, Rize | fig, mandarin |

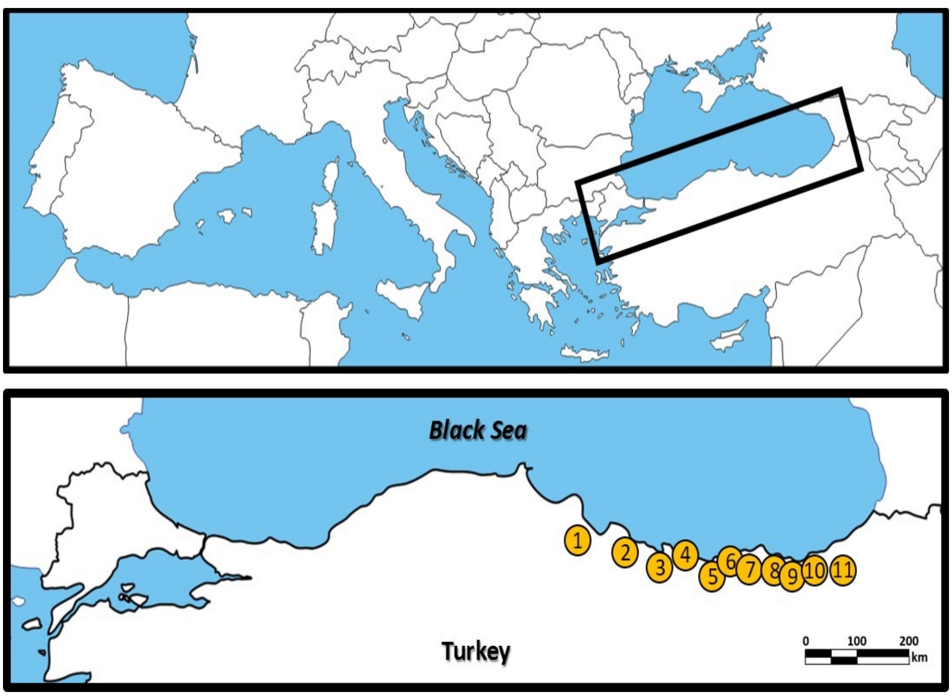


Figure 2. Localities visited to collect fruit samples to search *Ceratitis capitata* (Wiedemann, 1824) presence along the Black Sea Region of Turkey.

## Results and Discussion

In total, more than 500 adults emerged from the fruit collected from 50 different sites. The ENM performed better than a random prediction (AUC > 0.5). The average test AUC for the replicate runs was 0.957, and the standard deviation was 0.054. These results indicate that performance of the model was very good (Gassó et al., 2012). The prediction of current bioclimatic conditions largely matched the known geographic distribution of *C. capitata* which is very near to equilibrium with climate and inhabits coastal areas of Turkey. The percentage contribution suggested that 'mean temperature of coldest quarter' (BIO11) (45%), 'precipitation of coldest quarter' (BIO19) (32.6%), and 'precipitation of driest quarter' (BIO17) (6.5%) were the most significant bioclimatic variables in predicting the present potential distribution of *C. capitata*.

According to our model, *C. capitata* is potentially present along the Black Sea coast, particularly in the eastern part (Figure 3a). Additionally, the potential distribution of *C. capitata* under projected future bioclimatic conditions tends to expand as a response to future climatic change (Figure 3b, c).

From 136 of 170 (80%) fruit samples collected from the localities where the model predicted a relatively higher probability of *C. capitata* occurrence (Eastern Black Sea Region, Figure 2), a total of 49 adult *C. capitata* emerged from pupae. Localities where *C. capitata* adults emerged were in Samsun, Ordu and Trabzon (localities 1, 2, 3, 4, 8 and 9, Table 2, Figure 2). Thus, in parallel to the predictions of the ENM and for the first time, we demonstrated that *C. capitata* has invaded the Black Sea Region of Turkey.

The number of generations produced by the pest is 4-5 in the Aegean Region and 7-8 in the Mediterranean Region, and oviposition ceases when the temperature drops below 17°C (Bergsten et al., 1999; USDA, 2003; BKU, 2016; UF-IFAS, 2016). The minimum and optimum temperatures for larval emergence are 11 and 25°C, respectively. The minimum and maximum temperatures for the pupal stage are 9.7 and 35°C, respectively, whereas the optimum temperature is between 22 and 30°C (Shoukry & Hafez, 1979; Bergsten et al., 1999; USDA, 2003). Development of egg, larva and pupa stages slows down or ceases below 10°C (Bergsten et al., 1999; USDA, 2003; BKU, 2016). Thus, temperature is one of the most significant limiting factors and our results suggested the same. This is not a surprising result for insect species in general because their metabolic rates are directly tied to environmental temperature (Taylor, 1981; Pedigo & Rice, 2009; O'Connor et al., 2011).

Additionally, our model suggested that the precipitation can be responsible of the current distribution pattern of *C. capitata*. This result can be explained by the high correlation between temperature and precipitation in the Mediterranean (Tanarhte et al., 2012).

We visited the localities in the eastern Black Sea Region that were expected to be invaded by the Mediterranean fruit fly according to the ENM and we found the pest in these localities. To the best of our knowledge, this study is the first attempt to predict current and future distribution of *C. capitata* in Turkey. We cannot conclude that the model used was adequate to predict the exact distribution of the pest in Turkey; however, it successfully predicted its distribution in eastern Black Sea Region. Wider sampling is needed to test total success of the model.

This study is a first record of *C. capitata* range expansion through northern Turkey. We did not conduct any study to detect the size of the populations or the damage ratio in the region, but we found that *C. capitata* is widely established in the Black Sea Region, which suggests that invasion is not recent. Dispersal speed of *C. capitata* is reported to be 20 km/yr (Harris & Olalquiaga, 1991; Israely et al., 2005; Meats & Smallridge, 2007). Therefore, if this has not already happened, *C. capitata* is likely to spread to other countries in the eastern Black Sea basin in the near future.

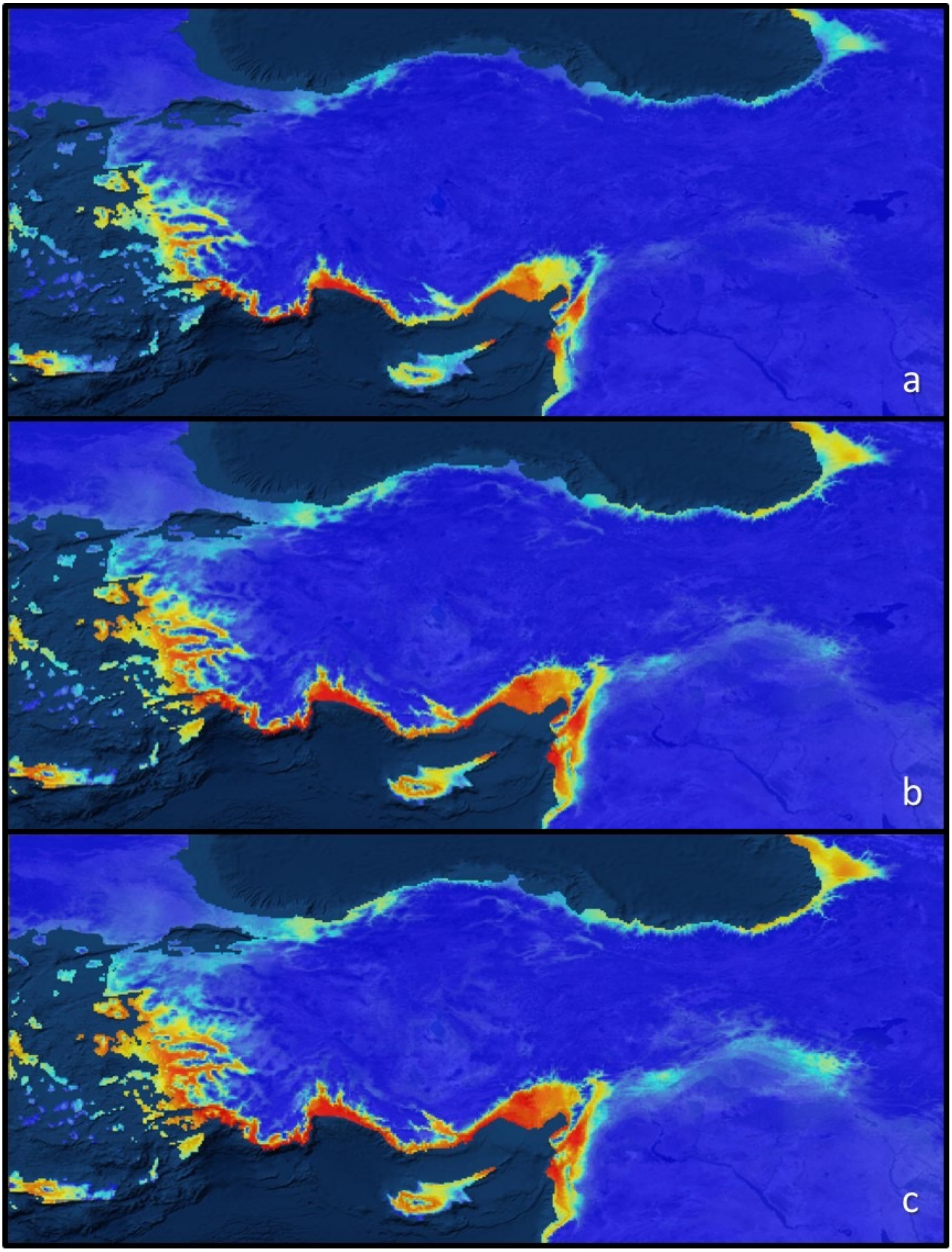


Figure 3. Distribution of *Ceratitis capitata* (Wiedemann, 1824) in (a) present day, (b) 2050, (c) 2070 according to the ecological niche model used. Warmer colors indicate areas of relatively higher suitability.

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