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Predicting the geographic distribution habitats of *Schizomyia buboniae* (Diptera: Cecidomyiidae) and its host plant *Deverra tortuosa* (Apiaceae) in Egypt by using MaxEnt modeling

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Abstract

Background: In some localities of the Mediterranean coast and the Nile land region, the gall midge *Schizomyia buboniae* Frauenfeld, 1859 (Diptera: Cecidomyiidae) induce small barrel-shaped galls on the stem of *Deverra tortuosa* (Desf.) DC. (Family: Apiaceae). Host plants interact with several insects in a different manner. The current work studies the interaction of *S. buboniae* with *D. tortuosa*. Furthermore, the present work predicted the distribution of *S. buboniae* and its host plant *D. tortuosa* in Egypt by using MaxEnt modeling, in addition to the effect of elevation and vegetation cover on its distribution.

Results: The predominance of *S. buboniae* occurred during late winter to spring. The *S. buboniae* larvae are occasionally attacked by endoparasitoids of the genus *Inostemma* (Platygastridae). There was a significant positive correlation between the number of galls per plant and the plant cover within the study localities. Meanwhile, there was no significant correlation between the number of galls per plant and the altitude within the study localities. Also, the high temperature and altitude were the most important predictors for the habitat distribution of *S. buboniae* and its host plant *D. tortuosa*. The predicted distribution range size for *S. buboniae* is less than the total predicted distribution range size for *D. tortuosa*.

Conclusions: The current study suggests that the gall inducer prefers large plants more than small ones. The present study suggests that the habitat distribution patterns of *S. buboniae* and its host plant *D. tortuosa* in Egypt can be modeled using a small number of occurrence records together with environmental variable layers for the study area through the maximum entropy modeling technique.

Keywords: Galls, Prediction, Mediterranean coast, Interactions, Climatic variable

Background

Plant galls and other types of disease found on host plants have motivated many researchers to conduct studies into the mechanism of gall formation (Hori, 1976). Plant galls are neo-shaped structures in plant tissues arising from cellular hyperplasia and hypertrophy that can situate in various plant organs such as the stems, leaves, flowers, fruits, roots, and axillary buds (Ascendino & Maia, 2018; Santos, Hanson, Maia, & Mehltreter, 2018). Galls are most often observed as swollen, large growths on a leaf, branch petiole, or twig (Royer & Rebek, 2013). These are induced by various organisms such as fungi, bacteria, viruses, nematodes, mites, and insects (Barbosa & Wagner, 1989). Gall

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formation involves an intimate parasitic interaction between the gall maker and its host plant (Rocha et al., 2013). Galls supply nutrition, assurance, and shelter to the gall-inducing insects or their offspring (Ascendino & Maia, 2018).

Gall-inducing insects are remarkable bioindicators of any alters in the environment and habitat quality due to their host specificity, close-fitting habit, abundance, and easy localization (Julião, Fernandes, Negreiros, Bedê, & Araújo, 2005; Santana & Isaias, 2014). The diversity of gall-inducing insects reflects the conservation status of an ecosystem (Santana & Isaias, 2014).

Gall-inducing insects may provide a vital tool to evaluate habitat quality and restoration (Kamel, 2021). Their species richness was used as indicators of forest age and health (Fernandes, Almada, & Carneiro, 2010), and they were used as bioindicators of habitat restoration in a degraded land of Atlantic Forest (Moreira, Fernandes, Almada, & Santos, 2007).

A question of great interest is how gall-inducing insects are affected by several biotic and abiotic variables. The plant structural complexity, the altitudinal/latitudinal gradient, and the host plant geographical range size are the main factors that may affect the richness and diversity of gall-inducing insects (Fernandes et al., 2010; Kamel, 2012; Roininen et al., 2006). The physical structure of the aerial vegetation parts of the host plant affects the community structure of gall insects (Araújo, De Paula, Carneiro, & Schoereder, 2006a). Additionally, leaf size and shoot diameter may also affect the gall induction (Fritz, Gaud, Sacchi, & Price, 1987; Yamazaki & Ohsaki, 2006).

Gall-forming species is about 2% of the total named insect species (Dreger-Jauffret, 1992; Raman, Schaefer, Withers, & Enfield, 2005). Cecidomyiidae (Diptera: Nematocera) are the youngest, largest, and most diverse subfamily of gall midges that hold more than 6651 species (Gagné & Jaschhof, 2004; Gagné & Jaschhof, 2021). Cecidomyiidae have a cosmopolitan distribution; therefore, Cecidomyiidae is estimated to be the richest taxon in the kingdom Animalia with over 1.8 million species worldwide (Hebert et al., 2016). Gall-forming insects have an important role in pollination (Borges, 2015). Some of Cecidomyiidae gall midge species are economically important; it can make damage to agricultural plants (Darvas, Skuhravá, & Andersen, 2000) and to forest trees (Skuhravá & Roques, 2000). Some galls contain tanins which are used for tanning and for medicinal purposes from India to Algiers (Gerling, Kugler, & Lupo, 1976).

Recently, many gall midges were recorded inducing different types of plant galls in several regions of Egypt (Doğanlar & Elsayed, 2013; Doğanlar & Elsayed, 2015; Elsayed & Karam, 2016; Elsayed, Karam, & Tokuda, 2017; Elsayed, Skuhrava, Karam, Elminshawy, & Al-Eryan, M. A., 2015; Kamel, 2012; Kamel, 2021; Kamel, Semida, & Abdel-Dayem, 2012).

Schizomyia is a genus of gall midges. It is characterized by a cosmopolitan distribution (Elsayed et al., 2019; Elsayed, Lin, Yang, & Tokuda, 2020; Elsayed, Yukawa, & Tokuda, 2018; Frauenfeld, 1859). In the coastal desert habitat, *Schizomyia buboniae* (Frauenfeld, 1859) induces berry-like galls on the stems of *Deverra tortuosa* (Skuhravá, Skuhravý, & Elsayed, 2014). It was collected before in some areas of Egypt such as Suez, Wadi Degla Protectorate in Cairo, and Burg El-Arab (Alexandria). (Frauenfeld, 1859; Skuhravá et al., 2014). This species is univoltine, with galls apparent on the host from late f February to early April. Pupation takes place inside the gall, and adults emerge from March to April (Dorchin & freidberg, 2011; Skuhravá et al., 2014).

Deverra tortuosa (Desf.) DC. (Family: Apiaceae) is recorded as a common associate in most plant communities located in the coastal and inland desert habitats (Serag, Khedr, & Amer, 2020). *Deverra tortuosa* is one of the most important medicinal plants in Egypt. It is utilized in folk medicine as a diuretic, carminative, antiasthmatic, and analgesic against hypertension, constipation, fever, headache, and bites (Azzazi, Afifi, Tammam, & Sheikh Alsouk, A., 2015; El-Mokasabi, 2014). *D. tortuosa* resists against intestinal parasites and stomach pain (Azzazi et al., 2015). The *Deverra* extracts showed high scavenging and anti-oxidant properties under stress conditions (El-lamey, 2015a). *D. tortuosa* has high palatability for several grazing animals (Boulos, 2000). The plant grows in desert wadis and stony and sandy plains, and it is located in Egypt, Palestine, Saudi Arabia, Libya, and Tunisia (Boulos, 2000).

Species distribution models (SDMs) are an efficient tool for assessing the potential for species to exist in regions not previously surveyed (Guisan & Thuiller, 2005). These models have been used for providing a baseline for predicting a species' response to landscape variance and/or climate change (Araújo, Thuiller, & Pearson, 2006b) and for recognizing the important areas for conservation (Wilson, Westphal, Possingham, & Elith, 2005). Several studies indicated that a statistical mechanics approach as the MaxEnt technique performs very well even with small samples (Hernandez, Graham, Master, & Albert, 2006; Phillips, Anderson, & Schapire, 2006). Some studies were performed using species distribution models for predicting the geographic distribution of various species in Egypt (El Alqamy et al., 2010; Kamel et al., 2012).

Therefore, the main goal of this study was to investigate the interaction of *S. buboniae* with *D. tortuosa* in some regions of the Mediterranean coast in Egypt and study the effect of elevation and vegetation cover on gall

Table 1 The recorded locations of *D. tortuosa* in Egypt

No.	Location	Coordinates		References
		Latitude	Longitude	
1	Wadi Degla, Cairo	29.96	31.32955	(Chrtek, Osbornova, & Sourkova, 1967)
2	Wadi El Natrun, El Alamein Road	30.657	29.603	(El-Lamey, 2015b)
3	Ras El Hekmah	31.1179	27.823	(Chrtek et al., 1967)
4	Wadi Hoff	29.916	31.3779	(Chrtek et al., 1967)
5	Cairo-Suez Road	30.118	31.635	(Chrtek et al., 1967)
6	Cairo-Suez Road	30.1042	31.7443	(Chrtek et al., 1967)
7	Cairo-Suez Road	30.0923	31.8682	(Chrtek et al., 1967)
8	Cairo-Suez Road	30.08816	31.9444	(Chrtek et al., 1967)
9	Wadi Sudr, Ras Sudr	29.500	32.700	(El-Lamey, 2015b)
10	Wadi Sudr, Ras Sudr	30.300	30.1000	(El-Lamey, 2015b)
11	Wadi Sudr, Ras Sudr	30.700	29.400	(El-Lamey, 2015b)
12	18 km west of Mersa Matruh	31.250	27.387	(El-Lamey, 2015b)
13	46 km coastal road before Mersa Matruh	31.1337	27.666	(Chrtek et al., 1967)
14	Ras El Hekma	27.816	31.887	(Chrtek et al., 1967)
15	Wadi Natrun	30.338167	30.406389	(Chrtek et al., 1967)
16	Cairo-Alexandria Desert Road	30.392	30.376	(Chrtek et al., 1967)
17	Pyramids, Giza	29.980	31.129	(Chrtek et al., 1967)
18	Pyramids, Giza	29.982	31.132	(Chrtek et al., 1967)
19	Ismailia City	30.6043	32.2578	(Chrtek et al., 1967)
20	4 km from Ain Soklma	29.639	32.3078	(Chrtek et al., 1967)
21	Helwan	29.8404	31.2983	(Chrtek et al., 1967)
22	WADI Qusseib, coast of Gulf of Suez	29.0515	33.2051	(Chrtek et al., 1967)
23	Moghra Oasis	30.2506	28.9367	(Chrtek et al., 1967)
24	Wadi Aber of Gebl Ataqa	29.9259	32.3631	(Chrtek et al., 1967)
25	Sakkara, Cairo	29.8590	31.1352	(Chrtek et al., 1967)
26	6 October	30.90133	29.544444	(Abd El-Ghani, Bornkamm, El-Sawaf, & Turky, 2011)
27	Farsh Shoeab	28.5527	33.9668	(Kamel et al., 2012)
28	Wadi El-Deer	28.55776	33.97799	(Kamel et al., 2012)
29	Wadi El Arbain	28.55269	33.94931	(Kamel et al., 2012)
30	Wadi Telah	28.5765	33.92702	(Kamel et al., 2012)
31	El-Gabal El-Molawan	28.58151	34.06413	(Kamel et al., 2012)

induction. Furthermore, this study tried to estimate the geographic distribution habitats of *S. buboniae* and its host plant *D. tortuosa* in Egypt using the maximum entropy modeling technique (MaxEnt) for searching the suitable areas of the gall maker *S. buboniae* and its host plant *D. tortuosa* in Egypt, which should be the important areas for conservation.

Methods

Study area

The floral territories of Egypt may be divided into the Mediterranean coast, the Nile land, and the deserts and mountains (El Hadidi & Hosni, 1996). Egypt's Mediterranean coast (north coast) extends from Sallum for approximately 970 km east to Rafah, with an approximate width of 15–20 km in a north-south direction (Hadidi, 1981). According to Zahran, El Demerdash, and Mashaly (1985) and Zahran, El-Demerdash, and Mashaly (1990), the north coast is ecologically divided into three sections; western (the Mareotis, spreading for 550 km between Sallum and Alexandria), middle (deltaic, spreading for 180 km between Alexandria and Port Said), and eastern (Sinaitic, spreading for 220 km between Port Said and Rafah).

The current study was conducted in some regions of the Mediterranean coast, in addition to some localities in the Nile land region. The chosen sampling sites for *D. tortuosa* were El Sadat City, El Nubariyah, Wadi El Natrun, El Amria, and El Alamein City (Fig. 6). The study sites were visited periodically in the period from February 2019 to June 2020, once every 2 months.

Table 2 Definitions of the climatic variable abbreviations

	Variable definition
Bio1	Annual mean temperature
Bio2	Mean diurnal range (mean of monthly (max temp − min temp))
Bio3	Isothermality (P2/P7) (×100)
Bio4	Temperature seasonality (standard deviation × 100)
Bio5	Max temperature of the warmest month
Bio6	Min temperature of the coldest month
Bio7	Temperature annual range (P5–P6)
Bio8	Mean temperature of the wettest quarter
Bio9	Mean temperature of the driest quarter
Bio10	Mean temperature of the warmest quarter
Bio11	Mean temperature of the coldest quarter
Bio12	Annual precipitation
Bio13	Precipitation of the wettest month
Bio14	Precipitation of the driest month
Bio15	Precipitation seasonality (coefficient of variation)
Bio16	Precipitation of the wettest quarter
Bio17	Precipitation of the driest quarter
Bio18	Precipitation of the warmest quarter
Bio19	Precipitation of the coldest quarter

Study plants

Deverra tortuosa (Desf.) DC. (Family: Apiaceae) is strongly aromatic glabrous and densely branched perennial shrub (30–80 cm), the plant stems are dichotomously branched, the leaves are caduceus, the flowers' petals are almost glabrous, and the fruit is sparingly hairy and globose (Boulos, 2000; Migahid, 1989). The recorded locations of *D. tortuosa* in Egypt are shown in Fig. 2 and Table 1.

Samples collection and identification

The size of each plant within the sample was measured using a tape meter for calculating plant cover (the ground area obscured by the plant's biomass when viewed from above) (Qi, Wei, Chen, & Chen, 2019) according to formula the (average width/100/2) ^2 × (22/7), in addition to the number of galls on different parts of the plant. Plant samples were identified according to Boulos (2000) and Migahid (1989). The immature stages of the gall inducer inside the galls were collected from the field and reared in the laboratory until the adults emerge; gall midge specimens are preserved in vials with 75% alcohol. The manipulation of the specimens was carried out under a stereomicroscope (model МБС-9, USSR) using a dissecting needle and a very delicate small forceps to prevent the sample distortions.

Data analysis

The collected data were analyzed using the SPSS computer package (PASW statistics ver.18, 2009). The Spearman correlation test was used to measure the relationship between altitude, plant size, and the number of galls per plant. Also, the one-way ANOVA test was used to compare the mean number of galls per plant between different localities.

Mapping and predicting distributions of plant species

The presence locations for *Deverra tortuosa* are recorded using GPS (Garmin XL 12). The Maxent software (version 3.3.1) is utilized to predict the potential distribution of the plant species using the presence data (recorded distribution) together with environmental variable layers for the study area, such as altitude, temperature, and moisture (Phillips et al., 2006; Phillips, Dudík, & Schapire, 2004).

Environmental data of the model

The model used various datasets as raster grids. Data were classified into climatic variables and topographical data. Nineteen bioclimatic variables (Table 2) are used to define the eco-physiological tolerances of a species (Graham & Hijmans, 2006). These were obtained from the WorldClim dataset (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005; http://www.worldclim.org/bioclim.htm). Altitude is the most topographic data that was utilized as a partial dataset (~1 km) from the Shuttle Radar Topography Mission (SRTM). Moreover, we obtained retrospective distributional data for *Deverra tortuosa* from published literature besides our reliable observational data. When specific geographic coordinates were not provided for a locality, we used maps and gazetteers to assign geographical coordinates to these records.

Statistical validation of the model

An extrinsic and independent test datasets were used to assess the predictive performance of the model (randomly data partition into 75% of the points was used to build the model and to predict species "training data" and 25% for model testing "testing data"). Statistical validation of the model was performed by comparing the extrinsic omission rates (i.e., proportion of test localities falling outside the prediction for each algorithm) with calculations of the area under the curve (AUC) of the receiver operating characteristic (ROC). The area under the curve (AUC) is used as a measure of the accuracy of the model (Phillips, 2016). The AUC ranges from 0 to 1. An AUC of 0.5 indicates a model that is no better than random, while an AUC of 1 indicates a perfect model (Phillips et al., 2004; Phillips et al., 2006). The current study used the AUC classification system provided by Hosmer, Lemeshow, and Cook (2000). That system classifies the AUC values as follows: 0.5–0.6 = no discrimination, 0.6–0.7 = poor discrimination, 0.7–0.8 = acceptable discrimination, 0.8–0.9 = excellent

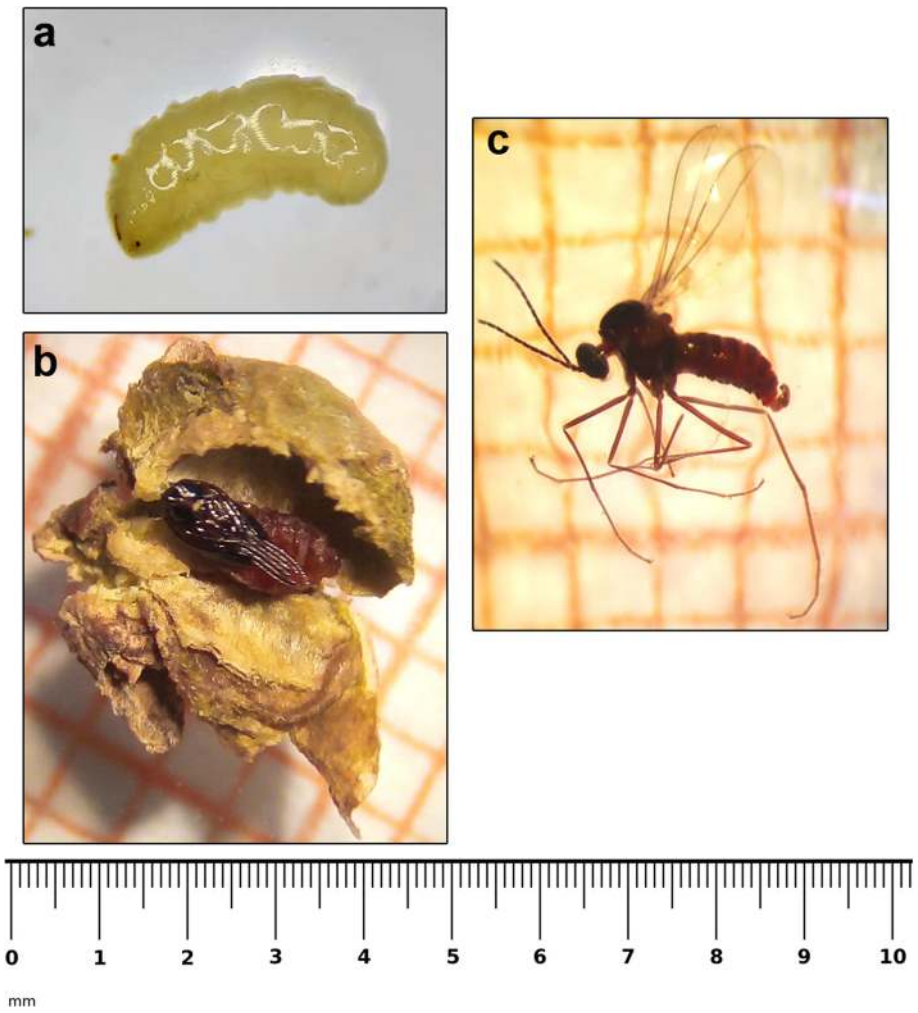


Fig. 1 The gall midge *Schizomyia buboniae* Frauenfeld, 1859 (Diptera: Cecidomyiidae). **a** Ethanol-preserved larvae (3 mm), **b** pupa (3 mm), and **c** adult (2.5 mm)

discrimination, and 0.9–1.0 = outstanding discrimination (Hosmer et al., 2000). The percentage contribution of each variable to the final model was provided by MaxEnt; the contribution values are determined by the increase in gain of the model provided by each variable (Phillips et al., 2006). The MaxEnt model's internal jackknife test was used to determine which variables contribute most to the model development.

Table 3 Gall induction on *Deverra tortuosa* within the study area

Location	Number of host plant	Number of galls
El Sadat city	34	212
Wadi El Natrun	5	12
EL Nubariyah	2	4
El Amria	6	17
El Alamein	44	147
Total	**91**	**392**

Results

Gall morphology and life history of *Schizomyia buboniae* (Diptera: Cecidomyiidae)

The gall midge *S. buboniae* (Fig. 1) induced 392 galls on 91 individuals of *D. tortuosa* within the study area (Table 3). The galls (Fig. 2) develop on the stems of *Deverra tortuosa* and appear as globular aggregations of 10–50 small barrel-shaped assemblages, resulting in a delicate berry-like structure, 1.5–3 cm in diameter. Each barrel-shaped chamber of the gall contains a single larva. Pupation takes place inside the gall (Fig. 1), and one generation is recorded during a year. The fresh gall is green in February and soon converts to yellow and then brown after adult gall midges emerge from it in early April to the end of May. The *S.*

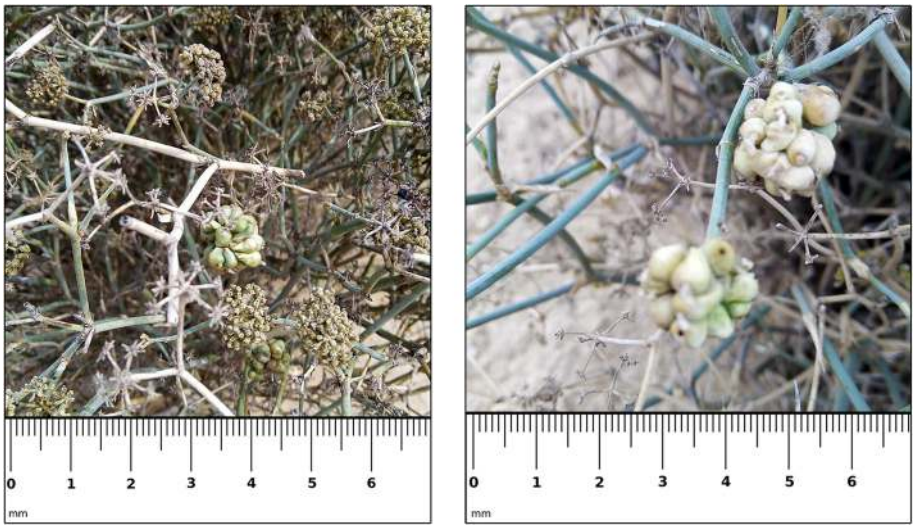


Fig. 2 The berry-like galls of *Schizomyia buboniae* (1.5–2.5 mm)

buboniae larvae are occasionally attacked by endoparasitoids of the genus *Inostemma* (Platygastridae) (Fig. 3).



Fig. 3 *Inostemma* sp. (Platygastridae) (2 mm)

Factors affecting the distribution of *Schizomyia buboniae* on *Deverra tortuosa*

Correlation between the number of galls per plant, plant cover, and altitude

There was a significant positive correlation between the number of galls per plant and the plant cover within the study localities (rs = 0.340, $P < 0.01$) (Fig. 4). Meanwhile, there was no significant correlation between the number of galls per plant and the altitude within the study localities (rs = −0.105, P =0.354).

Spatial distribution of the number of galls induced on Deverra tortuosa among different localities

There was a significant difference in the number of galls induced on *Deverra tortuosa* among different localities (El Sadat City, EL Nubariyah, Wadi El Natrun, El Amria, and El Alamein City) (F (4, 86) = 2.611, $P < 0.05$) (Fig. 5). El Sadat City showed the greatest mean number of galls per plant, 6.24, as compared to 2, 2.4, 2.83, and 3.34 at EL Nubariyah, Wadi El Natrun, El Amria, and El Alamein City, respectively.

The post hoc test according to Tukey's method is performed to test multiple comparisons between different study localities in the distribution of the number of galls induced on *Deverra tortuosa*. There was a significant difference between El Sadat City and El Alamein City equal to 2.89 ($P < 0.05$).

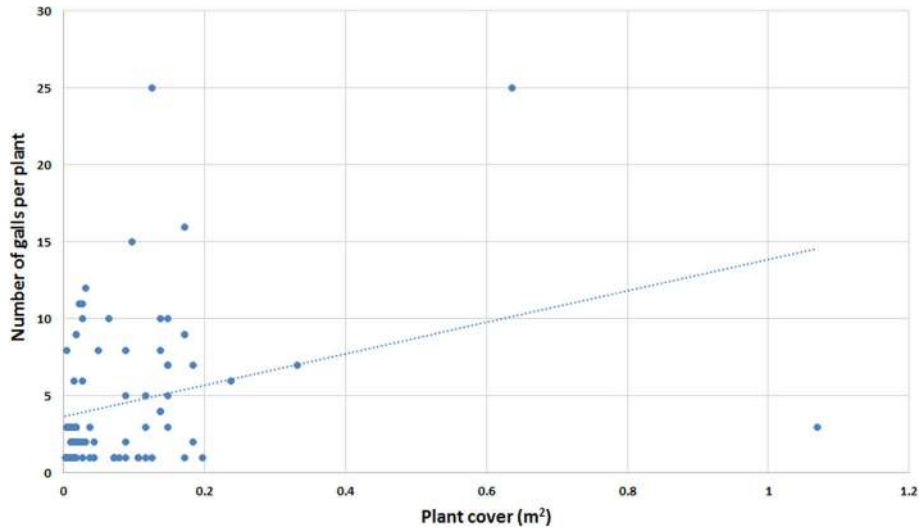


Fig. 4 The relationship between the number of galls per plant and the plant cover within the study localities

Spatial prediction model of the gall midge *S. buboniae* and its host plant *D. tortuosa* in Egypt

The predicted distribution range of S. buboniae and D. tortuosa in Egypt

The MaxEnt model for *S. buboniae* is shown in Fig. 6. The predicted distribution habitat of *S. buboniae* is mainly concentrated in some areas close to the Mediterranean coast, in addition to some areas in the Nile delta region and the Red Sea coasts. Five presence records were used for training and one for testing. The AUC (Fig. 7) for the training points was 0.994 and for the test points, it was 0.999, with a standard deviation of −1.000. The AUC was greater than 0.90, indicating outstanding discrimination for *S. buboniae*. The minimum training presence among training points was 57.207. At this threshold, the fractional predicted area was 0.013, and the omission rate for test points was 0.000. The model classifies the test points correctly significantly more than a random model (P <0.001).

The MaxEnt model for *D. tortuosa* is shown in Fig. 8. The predicted distribution habitat of *D. tortuosa* covers wide regions of the Mediterranean coast, in addition to some localities in the Nile land region, the Red Sea coast, and South Sinai. Twenty-five presence records

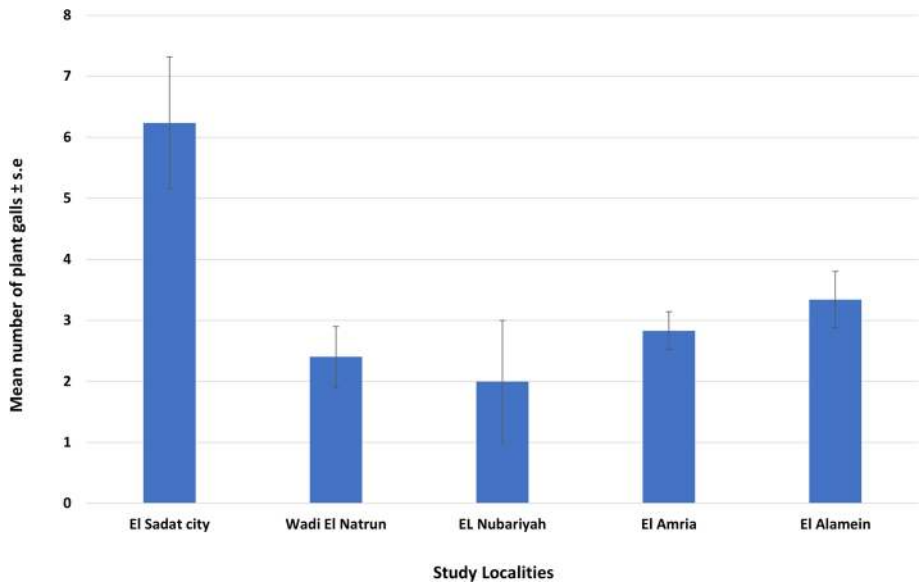


Fig. 5 The spatial pattern of gall distribution on the *Deverra tortuosa* among different study localities (F (4, 86) =2.611, P < 0.05)

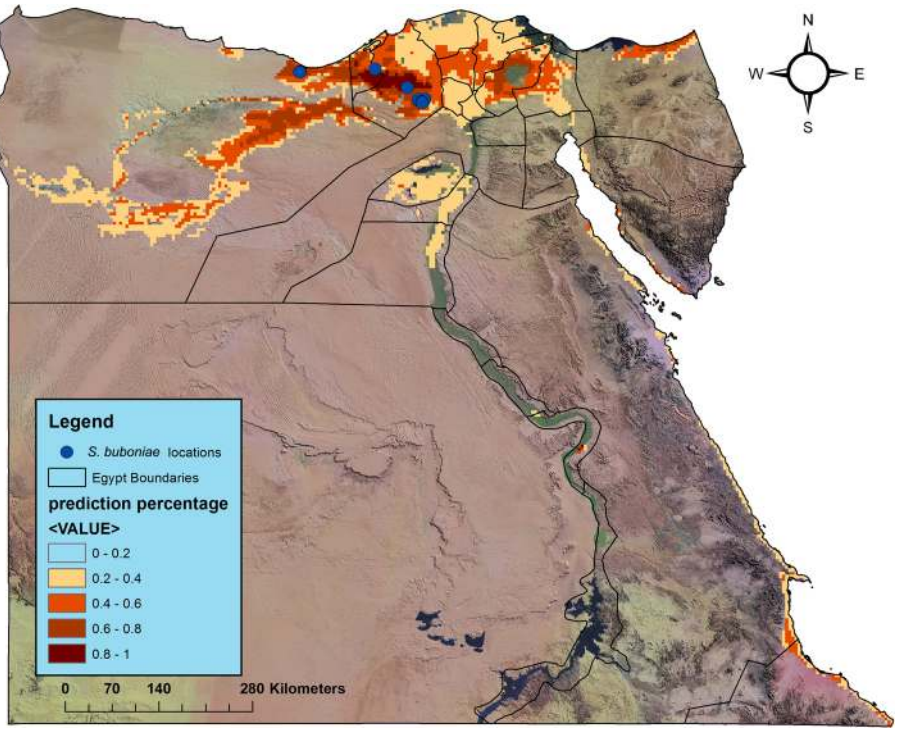


Fig. 6 The predicted distribution range of the *S. buboniae* according to the MaxEnt model (map source: IESR, GIS unit, and Google Maps https://www.google.com.eg/maps/@27.4846067,31.3939551,6z)

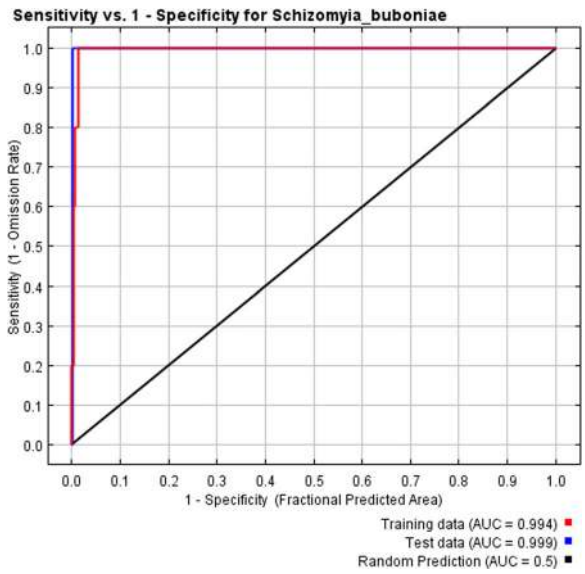


Fig. 7 The predicted distribution range of the *D. tortuosa* according to the MaxEnt model (map source: IESR, GIS unit, and Google Maps https://www.google.com.eg/maps/@27.4846067,31.3939551,6z)

were used for training the model and 8 for testing. The AUC (Fig. 9) for the training points was 0.941, and for the test points, it was 0.934, with a standard deviation of 0.017. The AUC was greater than 0.90, indicating outstanding discrimination for *D. tortuosa*. The minimum training presence among training points was 2.115. At this threshold, the fractional predicted area was 0.415, and the omission rate for test points was 0.000. The model classifies the test points correctly significantly more than a random model (P <0.001).

Effect of predictor variables in the representation of the MaxEnt model for *S. buboniae* and *D. tortuosa* in Egypt

According to the analysis of the variables using the percent contribution heuristic test (Fig. 10), *S. buboniae* showed high sensitivity to altitude, temperature seasonality (BIO4), precipitation of the warmest quarter (BIO18), precipitation seasonality (BIO15), annual mean temperature (BIO1), isothermality (BIO3), and mean temperature of the wettest quarter (BIO8), with contribution percentage equal to 45%, 18%, 13%, 11%, 7%, 4%, and 2%, respectively.

The MaxEnt model's internal jackknife test of variable importance showed that altitude was the most important predictor of *S. buboniae* habitat distribution. This variable showed higher gains that included the most information as compared to the other variables.

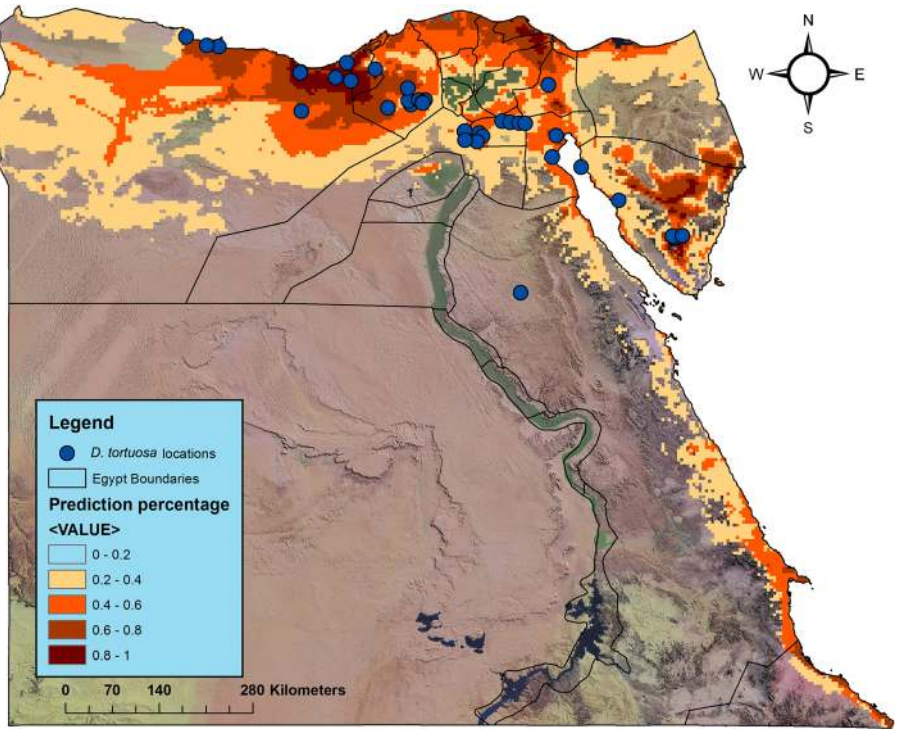


Fig. 8 Training data (AUC = 0.994) and test data (AUC = 0.999) compared to random prediction (AUC = 0.5) in the receiver operating characteristic (ROC) curve for the representation of the MaxEnt model for *S. buboniae*

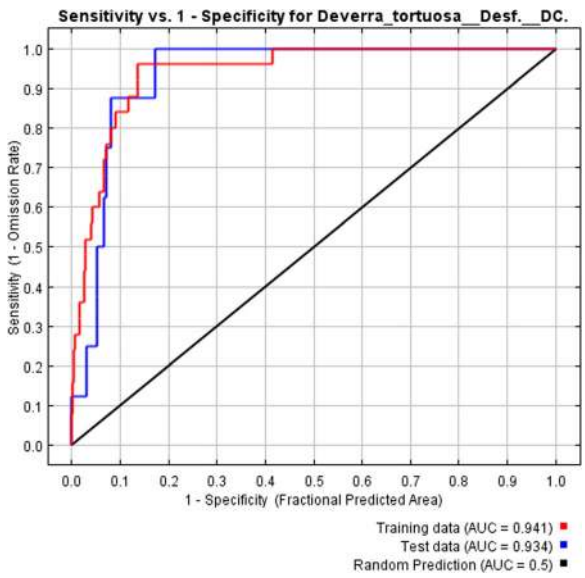


Fig. 9 Training data (AUC = 0.941) and test data (AUC = 0.934) compared to random prediction (AUC = 0.5) in the receiver operating characteristic (ROC) curve for the representation of the MaxEnt model for *D. tortuosa*

According to the analysis of the variables using the percent contribution heuristic test (Fig. 11), *D. tortuosa* showed high sensitivity to temperature seasonality (BIO4), precipitation of the warmest quarter (BIO18), precipitation seasonality (BIO15), temperature annual range (BIO7), mean temperature of the warmest quarter (BIO10), max temperature of the warmest month (BIO5), and precipitation of the wettest quarter (BIO16), with contribution percentage equal to 54%, 12%, 9%, 7%, 7%, 6%, and 5%, respectively.

The MaxEnt model's internal jackknife test of variable importance showed that max temperature of the warmest month (BIO5) and precipitation of the warmest quarter (BIO18) were the most important predictors of *D. tortuosa* habitat distribution. These variables presented higher gains that included the most information as compared to the other variables.

Discussion

A question of great concern in herbivory is how plant traits affect attacks by phytophagous insects (Prado & Vieira, 1999). According to Price (1991), the plant vigor hypothesis proposes that more potent, energetic, fast-growing plants will be preferred by several types of herbivores that depend on high meristematic activity, units of large size, or some chemicals of nutritional property related with vigor. The current study suggests that the

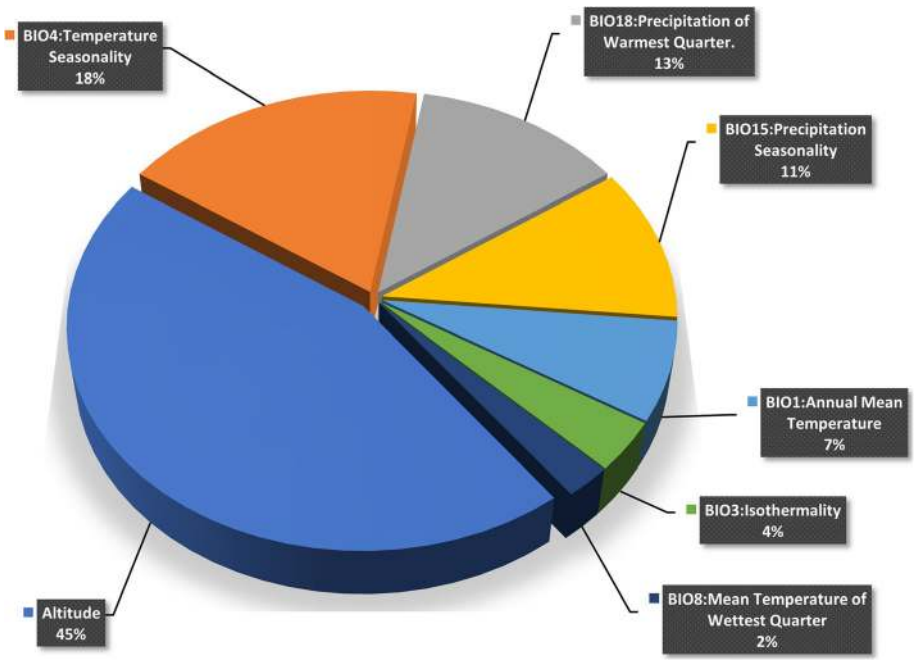


Fig. 10 Analysis of variables contributes to the prediction distribution model of *S. buboniae*

gall inducer prefers the large plants more than the small ones which was clear from the positive correlation between the plant cover and the number of galls per plant. Therefore, the current study supports the plant vigor hypothesis in the case of *D. tortuosa*. It may be strongly attributed to the availability of resources provided by large plants, which supports the suggestions of Feeny (1975). Gall-inducing insects usually prefer large and fast-growing plant organs, such as shoots and leaves (Price, 1991). The current study showed that the stem of *D. tortuosa* is one of the most important parts of the plant subjected to gall induction. It may be strongly attributed to the large shoot diameter that may provide enough area for gall induction (De Bruyn, 1994). Also, the gall inducer prefers the more rewarding parts of the plant to form the gall (Whitham, 1978).

The current study suggests that the habitat distribution patterns of *S. buboniae* and its host plant *D.*

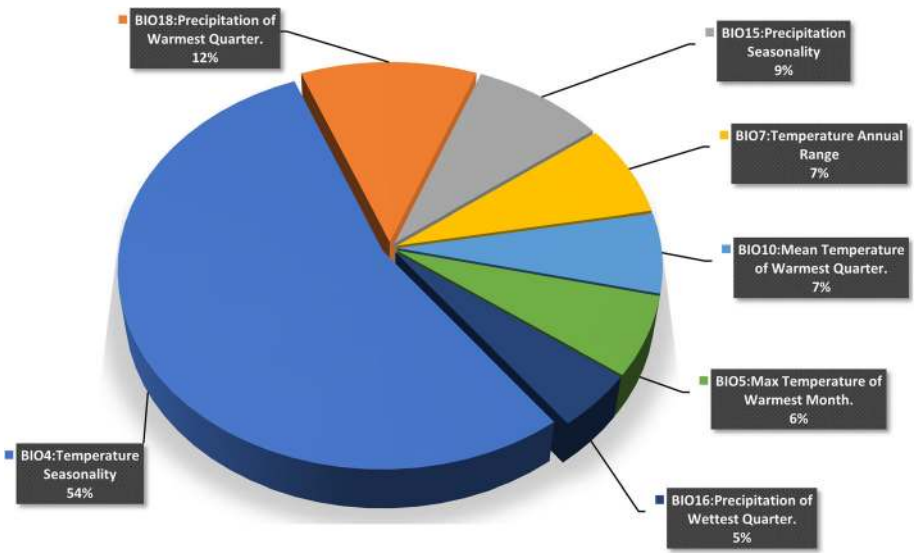


Fig. 11 Analysis of variables contributes to the prediction distribution model of *D. tortuosa*

tortuosa in Egypt can be modeled using a small number of occurrence records together with environmental variable layers for the study area through the maximum entropy modeling technique (MaxEnt). So, the present study agrees with the view of Hernandez et al. (2006) and Kamel et al. (2012) who suggested that the MaxEnt technique worked better for species with very small occurrence records that have relatively wide geographic distributions.

The present study suggested that the predicted distribution range size for *S. buboniae* is less than the total predicted distribution range size for *D. tortuosa*. The predicted distribution habitat of *S. buboniae* is mainly concentrated in some areas close to the Mediterranean coast, in addition to some regions in the Nile delta region. This agrees with the findings of Skuhravá et al. (2014) who reported that the distribution of *S. buboniae* is concentrated in Mediterranean regions, while the predicted distribution habitat of *D. tortuosa* covers a wider region of the Mediterranean coast, in addition to some localities in the Nile land region, the Red Sea coast, and South Sinai. This has concurred with the view of Kamel et al. (2012) and El-Lamey (2015b) who recorded *D. tortuosa* in different areas of South Sinai.

Gall-inducing insects are perfect models for studies on the specificity and ecological diversity due to their abundance, richness, and sessile habit (Santana & Isaias, 2014). They possess a high specificity to their host plants and have predictable responses to any changes in the environment (Fernandes et al., 2009).

So, the current study suggested that the gall midge *S. buboniae* can be a vital tool for biodiversity conservation due to its highly specific interaction with the host plant *D. tortuosa.*

The present study showed that altitude was the most important predictor of *S. buboniae* habitat distribution. This agrees with the findings of Semida (2006) and Kamel et al. (2012) who suggested that altitude is an important variable determining the distribution of gall-forming insects. Furthermore, max temperature of the warmest month (BIO5) and precipitation of the warmest quarter (BIO18) were the most important predictors of *D. tortuosa* habitat distribution. This has concurred with the view of Vasseur et al. (2014) who suggested that most plant species show increases in performance at greater mean temperatures.

Plant galls are remarkable for the association of a complex community of species, other than the gall inducer, belonging to diverse insect groups. These other species may be either parasites that cause the eventual death of the gall maker or "guests" of the gall former "inquilines" that obtain their nourishment from tissues of the gall (Sanver & Hawkins, 2000). The present study showed that the *S. buboniae* larvae are occasionally attacked by parasitic wasps of the genus *Inostemma* (Platygastridae, Hymenoptera), which is recorded in plant galls to benefit from the nutrients found in the plant tissue inside the gall. This agrees with the findings of Dorchin and Freidberg (2011) who reported that *Inostemma* sp. was endoparasitoids for the *S. buboniae* larvae which form stem galls in *D. tortuosa* in Israel. In contrast, Kamel et al. (2012) showed that *Inostemma* sp. was the principal gall maker which induced stem galls on *D. tortuosa* in Saint Katherine Protectorate, South Sinai. Therefore, this finding was incorrect according to our results.

Conclusions

The current study suggests that the gall-making insects prefer large plants more than small ones. The present study suggests that the predicted habitat of *S. buboniae* and its host plant *D. tortuosa* in Egypt can be modeled using a small number of occurrence records together with climatic variable layers for the study area through the maximum entropy modeling technique.

Based on our prediction results and analysis, it is so important to study more about plant gall induction in Egypt as a unique form of insect-plant interactions Additionally, we need to pay more attention to the suitable areas of the gall inducer *S. buboniae* and its host plant *D. tortuosa* in Egypt, which should be the important areas for protection.

Abbreviations

Alt: Altitude; AUC: Area under the curve; Bio1: Annual mean temperature; Bio10: Mean temperature of the warmest quarter; Bio11: Mean temperature of the coldest quarter; Bio12: Annual precipitation; Bio13: Precipitation of the wettest month; Bio14: Precipitation of the driest month; Bio15: Precipitation seasonality (coefficient of variation); Bio16: Precipitation of the wettest quarter; Bio17: Precipitation of the driest quarter; Bio18: Precipitation of the warmest quarter; Bio19: Precipitation of the coldest quarter; Bio2: Mean diurnal range (mean of monthly (max temp − min temp)); Bio3: Isothermality (P2/P7) (× 100); Bio4: Temperature seasonality (standard deviation × 100); Bio5: Max temperature of the warmest month; Bio6: Min temperature of the coldest month; Bio7: Temperature annual range (P5–P6); Bio8: Mean temperature of the wettest quarter; Bio9: Mean temperature of the driest quarter; Fig.: Figure; GIS: Geographical information system; m. a. s. l: Meters above sea level; MaxEnt: Maximum entropy modeling technique; *P*: Probability; ROC: Receiver operating characteristic; rs: Spearman correlation coefficient; Sig.: Significant; SRTM: Shuttle Radar Topography Mission

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Authors' contributions

MK, MMM, and SHR collected the data. ASB analyzed the results. MK and SHR interpreted the results of predicting the geographic distribution habitats of *Schizomyia buboniae* (Diptera: Cecidomyiidae) and its host plant *Deverra tortuosa* (Family: Apiaceae) in Egypt by using MaxEnt modeling. MK was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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