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Where in Europe is *Chrysomya albiceps*? Modelling present and future potential distributions

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Abstract

Chrysomya albiceps (Wiedemann, 1819), a species of blowfly (Diptera, Calliphoridae), historically distributed throughout Southern Europe, has recently dispersed to cooler regions in Europe, which is an intriguing phenomenon. In this work, we used Maxent software to formulate climate suitability using a machine learning technique to investigate this fact. The bioclimatic variables that best explained the climate suitability were Annual Mean Temperature (67.7%) and Temperature Annual Range (21.4%). We found that *C. albiceps* is climatically suitable for several parts of Europe, except for high altitude areas like the Swiss Alps. In warmer countries such as Portugal, Spain and Italy, the entire coastal territory was the most suitable for the species. Future scenario models show that in these eastern countries and some northern areas, climate suitability has increased. This increase is reinforced when comparing the gains and losses in climate suitability between the present-day model and the future scenario models. These changes are most likely caused by changes in temperature, which is the main explanatory factor among the tested variables, for the climate suitability. As one of the most important species in forensic contexts and a potential myiasis agent, the expansion of *C. albiceps* to new locations cannot be neglected, and its expansion must be carefully monitored.

Keywords

blowflies, Calliphoridae, climate suitability, European continent, Maxent, species distribution modelling

Introduction

As seen in recent years, the world is warmer and this phenomenon is influenced by anthropic activities such as fossil fuels burning, cement production, flaring, forest management and other land uses (Jia et al. 2019). According to the Intergovernmental Panel on Climate Change - IPCC (2021), an increase in the global average temperature is forecast for the coming years, considering the predicted scenarios. Those changes can modify global dynamics of the ecosystems by facilitating the invasion of exotic species, the dispersion of disease vector species and the emergence of agricultural pests (Wagner 2020), mainly insects (Samy et al. 2016; Iwamura et al. 2020; Wang et al. 2020). Predicting the distribution of insects in the context of climate change has become one of the great challenges of the 21st century.

Blowflies (Diptera, Calliphoridae) are a common group of insects, widespread throughout the world (Rognes 1997; Wolff and Kosmann 2016), including *Chrysomya albiceps* (Wiedemann, 1819). The biology and ecology of this species can be used to estimate the post-mortem interval of a corpse, as well as providing clues if the corpse has changed location (Martín-Vega et al. 2017). Beyond the forensic importance, understanding the potential distribution of this species is essential for the following reasons: 1) *C. albiceps* is a mechanical vector of pathogens. The species can also cause severe primary and secondary myiasis in livestock, domestic animals and humans (Zumpt 1965; Schnur et al. 2009; Sotiraki and Hall 2012); 2) sympatry with similar species such as *Chrysomya rufifacies* (Macquart, 1842) and *Chrysomya putoria* (Wiedemann, 1830) may induce taxonomic misidentification (Erzinclioglu 1987; Grella et al. 2015); 3) the species is a facultative predator of other blowflies in larval stage in Neotropical Region (Faria et al. 1999, 2007) and Paleartic Region (Ivorra et al. 2022); and 4) more studies are needed on their driving forces in specific geographical areas, especially at smaller scales (Hosni et al. 2022). Recently, research groups have used a maximum entropy algorithm with Maxent software (Phillips et al. 2006) to model current and future niche distributions of blowfly species (Mulieri and Patitucci 2019; Hosni et al. 2020), including *C. albiceps* (Hosni et al. 2022).

Maxent (Phillips et al. 2006; Phillips and Dudík 2008) has been used in recent years to estimate and predict scenarios of potential distribution of the species according to ecological niches favorable to the target species. This tool allows generating niche estimator models through bioclimatic data and the present occurrence of the species (Phillips et al. 2017). The tool is extremely popular and has been used systematically in recent years, as it has been shown to perform much better than other methods such as GARP and BIOCLIM (Elith et al. 2006). In this work, it was used to understand what the climate suitability of *C. albiceps* looks like, providing clues about its potential distribution under different climate scenarios.

The historical distribution of this species encompasses Africa, the Middle East, and Southern Europe (Séguy 1930–1932; Holdaway 1933). In the early 2000s, *C. albiceps* began to be identified in new areas of Europe (Povolny 2002; Grassberger et al. 2003). Since then, the distribution of the species has increased on the old continent towards other central and eastern European countries (Makovetskaya and Verves 2018). The recent and rapid dispersion of this species has generated two hypotheses: a) that the species' distribution is changing due to a more suitable climate (Povolny 2002; Gosselin and Braet 2008); b) that populations of *C. albiceps* are adapting to European winters (Makovetskaya and Verves 2018). Furthermore, the diapause mechanisms of the species are still not well understood (Michalski and Szpila 2016) and can also be a decisive factor in dispersion.

This study aimed to enhance our understanding of the climate suitability of *C. albiceps* and the climatic factors that influence its potential distribution. To achieve this, the study utilized geographic coordinates and bioclimatic variables to model the current and future distribution of *C. albiceps*. For that purpose, a maximum entropy machine learning technique was used. The discussion focused on the European region, given the recent expansion of the species in this continent.

Material and methods

Chrysomya albiceps records

A total of 671 occurrence records were obtained from scientific papers, monographs, and dissertations present in the following databases: https://www.biodiversitylibrary.org/, https://pubmed.ncbi.nlm.nih.gov/, https://scholar.google.com/, https://www.scielo.br/, https://www.elsevier.com/ and http://periodicos.capes.gov.br/. The keyword searched was "*Chrysomya albiceps*" (see references in Suppl. material 1). The Global Biodiversity Information Facility (www.gbif.org) was also used as a source of coordinates, with "species only" criterion and with the following filters: "material sample and preserved specimen" and "including coordinates". Some records from Brazil, using attractant traps by the first author, are included. Doubtful and repeated records were excluded. Records not coupled with collected specimens, records with photo-based identification and single records in remote areas (China, for example) were not used. Thereafter, the coordinates were refined with the filter of 20 km distance from each other using the package "spThin" in the RStudio program (Aiello-Lammens et al. 2015; RStudio Team 2021). The 20 km filter was used considering that species of the Calliphoridae family can reach distances of 3.5 km per day (Tsuda et al. 2009) and their adult life cycle can exceed several days (Norris 1965). After the coordinate refinement, 413 coordinates remained which were used to run the model (Fig. 1, see also Suppl. material 2). Although several coordinate points are lost after refinement, these steps are important to improve model fit.

Climatic data

Nineteen bioclimatic variables from the Worldclim database with a spatial resolution of 2.5 arc-min (Fick and Hijmans 2017) were used to generate the present day model. For the predictions of the future, the Global Climate Model IPSL-CM6A-LR of Coupled Model Intercomparison Project (CMIP6) (Boucher et al. 2020) was used, for two shared socioeconomic pathways (SSPs: SSP1-2.6 and SSP5-8.5) for two future

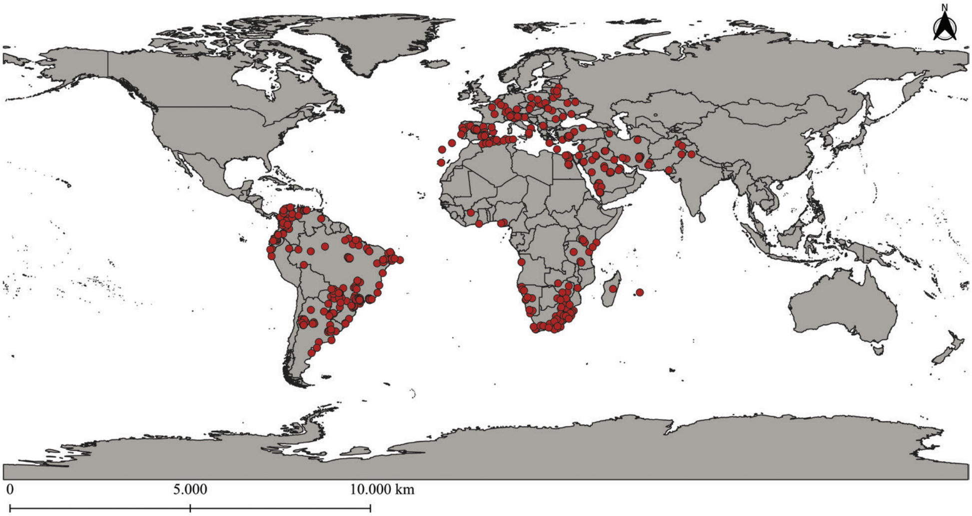

Figure 1. Occurrence points of *Chrysomya albiceps* recorded from the scientific literature and in the GBIF database.

periods (2041–2060 and 2061–2080). IPSL-CM6A-LR was used because it has high climatic sensitivity (Qin et al. 2021). Next, a dimensional reduction procedure and exclusion of highly correlated variables was initiated. This process is necessary to avoid contributions of variables that generate interpretation problems to the models (Hosni et al. 2022). A correlation between the variables was then performed in the R Program (RStudio Team 2021), using the raster package (Hijmans 2022) (see Suppl. material 3), to exclude highly correlated variables (r > 0.7). The best explanatory variable was chosen among the variables that correlated. The resulting variables used to fit the model were Bio1 (Annual Mean Temperature), Bio2 (Mean Diurnal Range, mean of monthly max temp – min temp), Bio7 (Temperature Annual Range), Bio12 (Annual Precipitation) and Bio15 (Precipitation Seasonality, Coefficient of Variation).

Modelling and model evaluation

The maximum entropy technique was used for modelling. The model input configuration (for present-day and future models) was: 100 replicates (70% calibration and 30% test), convergence threshold = 0, 0001, multiple regularizer = 1, maximum interactions = 500, and output in cloglog format with default prevalence = 0.6, for all potential models generated. The replicates were controlled using the Subsample replacement resampling method (Mulieri and Patitucci 2019), where data selected for testing cannot be selected for training. The performance of the generated models was evaluated using the Area Under the Roc Curve (AUC), a tool present in Maxent's output. Models with AUC > 0.75 are considered useful (Elith 2002). Model validation was assessed using True Skill Statistics (TSS). Finally, the Jackknife test was used to assess the importance of each variable for the construction of the present and future models.

Plotting

The suitability maps were plotted using the "Maximum training sensitivity plus specificity Cloglog threshold" (Liu and Shi 2020) obtained from the Maxent output (Threshold > 0.4). Climate suitability maps are reliably generated using this threshold (Liu et al. 2005). ArcGIS software was used to produce the maps (ESRI 2018). In Liu and Shi (2020), 4 suitability classes are used to visualize the maps. An additional class was created in the present study, namely: Unsuitable, Low, Medium, High, and Very High. To create these classes, we used the Reclassify function from ArcGis. To facilitate visualization of the European areas on maps, the region was divided into 4 sub-regions: Southern, Western, Eastern, and Northern. In addition, a comparison of climate suitability areas gains and losses between the different scenarios tested is provided (Hosni et al. 2022).

Results

The model generated from the potential distribution on present days had good performance (AUC = 0.886; sd = 0.007; TSS = 0.67). In this model, the variables that contributed the most to its construction were bio1 (67.7%) and bio7 (21.4%) (Fig. 2). In Fig. 3, it is shown how the predicted probability of presence changes according to the variation of bioclimatic variables. The variables with the highest gain were also bio1 and bio7 (see Suppl. material 3, Fig. 1).

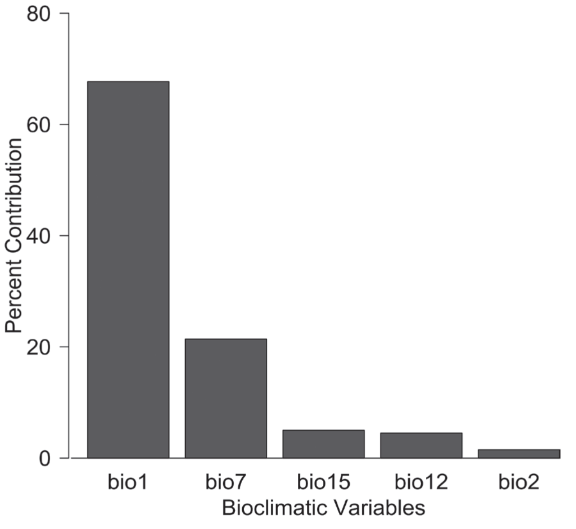

Figure 2. Relative contribution of bioclimatic variables to the construction of the current climate suitability model of the species *Chrysomya albiceps*. bio1 = Annual Mean Temperature, bio2 = Mean Diurnal Range, mean of monthly max temp – min temp), bio7 = Temperature Annual Range, bio12 = Annual Precipitation and bio15 = Precipitation Seasonality, Coefficient of Variation.

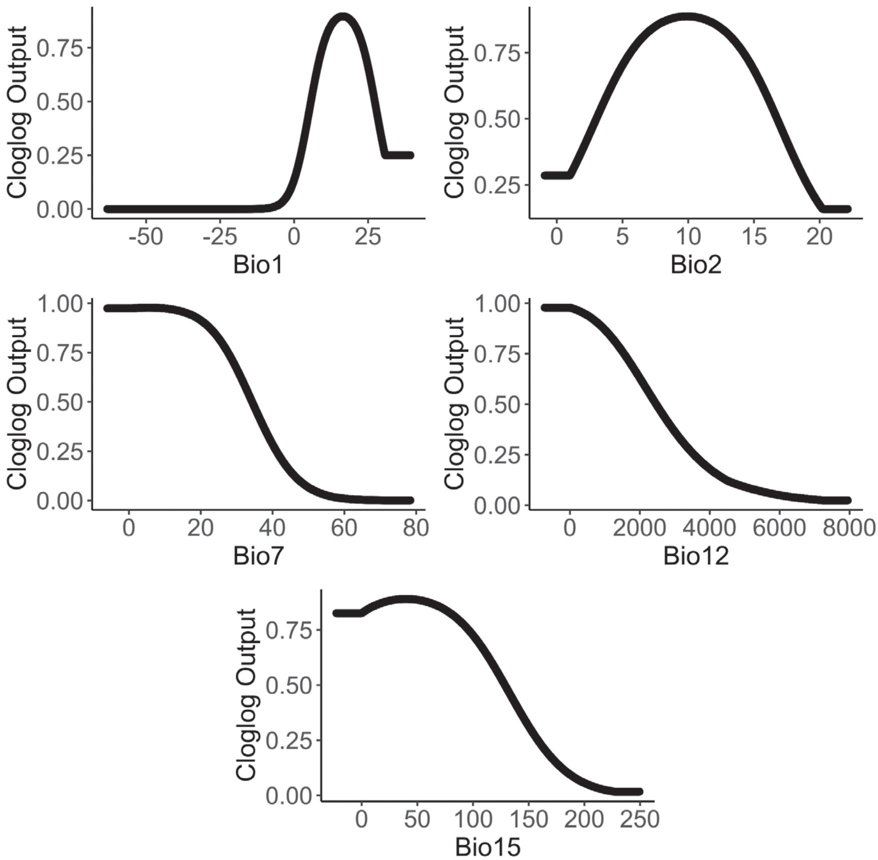

Figure 3. Response curves of the main bioclimatic variables in the construction of descriptive models of the climate suitability of *Chrysomya albiceps.* Bio1 = Annual Mean Temperature, Bio2 = Mean Diurnal Range, mean of monthly max temp – min temp), Bio7 = Temperature Annual Range, Bio12 = Annual Precipitation and Bio15 = Precipitation Seasonality, Coefficient of Variation.

Climate suitability for the species *C. albiceps* has been shown for the entire territory of Europe (Fig. 4), except for high altitude sites such as the Swiss Alps and Northern Europe. In warmer countries, such as Portugal and Spain, the entire coastal territory was shown to have a highly suitable climate for the occurrence of the species. Furthermore, nearby countries with higher latitudes, such as France and Belgium, also showed a highly suitable climate in their coastal areas. To the east, still in the Mediterranean area, Italy, Malta, Albania and Greece followed the same pattern. Colder countries like Poland have medium climate suitability in almost all their territory. Neighboring countries like Belarus and Lithuania have lower climate suitability, however, the occurrence of the species is already confirmed on their territories, (Lutovinovas and Markevičiūtė 2017; Makovetskaya and Verves 2018), which may mean that *C. albiceps* can establish itself even in countries with low climatic suitability.

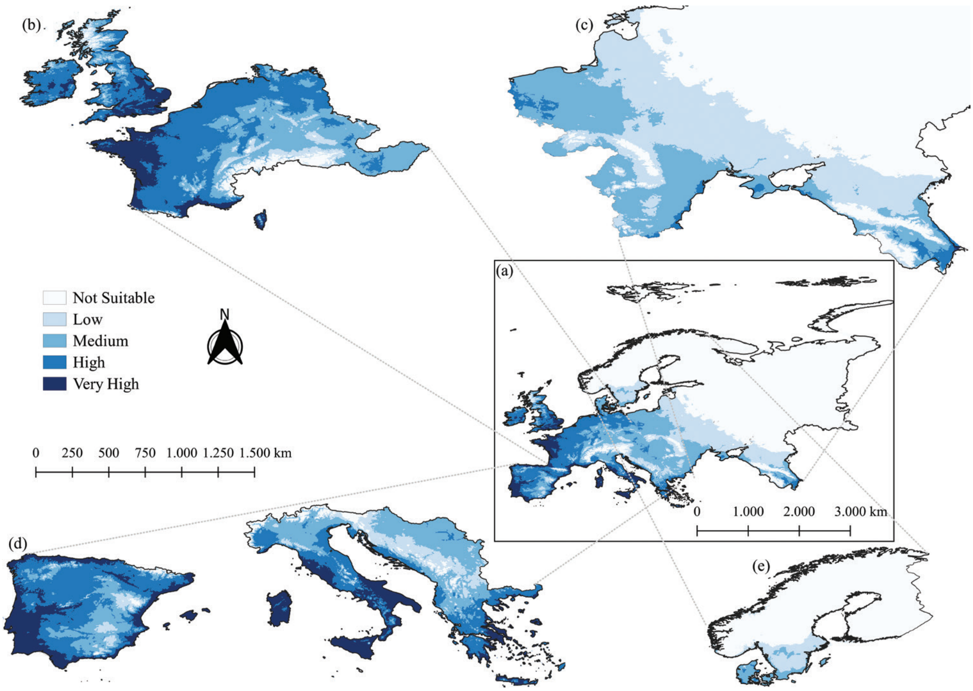

Figure 4. Climate suitability model of *Chrysomya albiceps* for present-day in the Europe (**a**) and sub-regions Western (**b**), Eastern (**c**), Southern (**d**) and Northern (**e**). Model ran in Maxent and figure redrawn in ArcGIS software.

The predictive future models of this work indicate that more areas in Eastern Europe will have increased climate suitability (Figs 5, 6, 7 and 8). Portugal, considering the 4 predictive scenarios, had little variation in the amount of climate suitability. Spain showed variation in all 4 scenarios. In many areas in the north-western and central parts of the country, the climate suitability decreased. However, territories in the east had the climate suitability increased from Medium to High. A part of the territories of France and Belgium lose much of their climate suitability, from very high to high. In the United Kingdom, considering the 4 scenarios, there is a tendency towards a decrease in the climate suitability (mainly in Ireland and Scotland). Interestingly, in Scotland, more areas fall into the Low/Medium category when the least optimistic scenarios are considered (Figs 6 and 8).

Variation in climate suitability was observed across the predictive scenarios, with greater improvements in the least optimistic scenarios compared to the optimistic scenarios (Fig. 9). The most substantial increases in climate suitability were detected in Eastern and Northern Europe. Conversely, the SSP1-2.6 and SSP5-8.5 scenarios of 2070 resulted in the most significant declines in climate suitability, with the loss distributed across all European sub-regions.

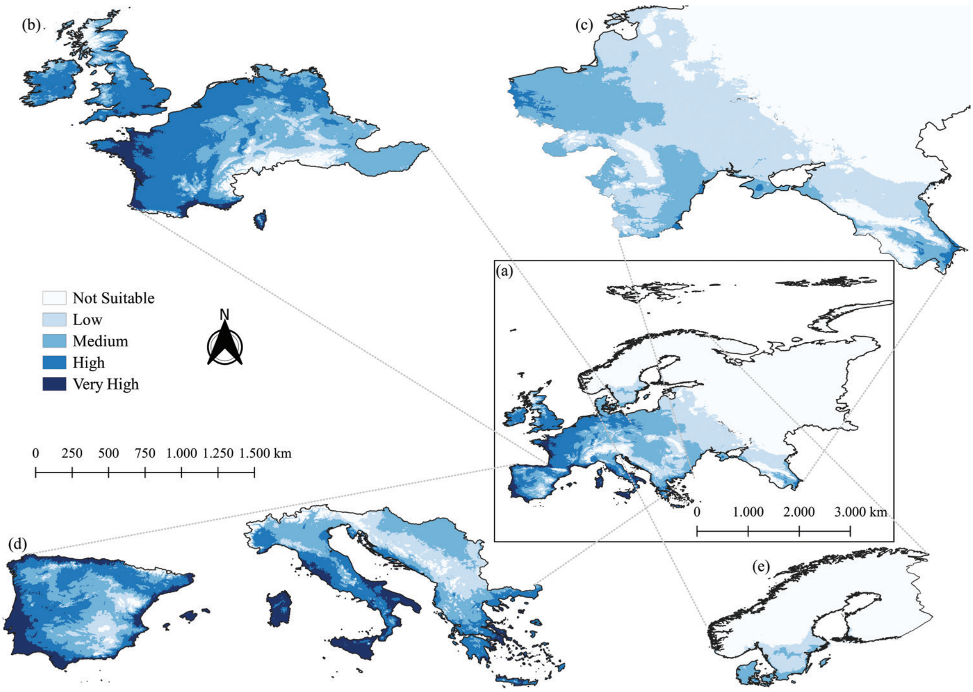

Figure 5. Climate suitability model of *Chrysomya albiceps* for the year 2050 in the most optimistic scenario (SSP1-2.6) in the Europe (**a**) and sub-regions Western (**b**), Eastern (**c**), Southern (**d**) and Northern (**e**). Model ran in Maxent and figure redrawn in ArcGIS software.

Discussion

Changes in the climate suitability for the occurrence of *C. albiceps* between present and future scenarios have been observed based on the tested variables in the models. These differences are particularly noticeable in Eastern Europe, towards the recent geographic expansion of the species. It appears that climate change is partly responsible for this dispersal, making cooler areas more prone to *C. albiceps* occurrence. The variables bio1 and bio7, which are related to temperature, contributed to almost 90% of the variance in the models. Therefore, changes in temperature (Figs 4, 5, 6, 7, and 8) are highly likely to explain the observed differences between present and future scenarios, such as the evenly distributed losses in climate suitability and the gains in suitability concentrated in Eastern Europe (Fig. 9). Consequently, *C. albiceps* may expand to new areas with climate suitability. For instance, according to Sivell (2021), the species is already considered a potential occurrence in the UK.

In the present work, it is demonstrated from a maximum entropy modelling that the most enlightening explanatory variables tested to understand the potential distribution of *C. albiceps* are the bio1 (Annual Mean Temperature) and the bio7 (Temperature Annual Range) (Figs 2 and 3). Not only that, but the generated model also demonstrates that if the bio1 is removed, the model loses much of its explanatory

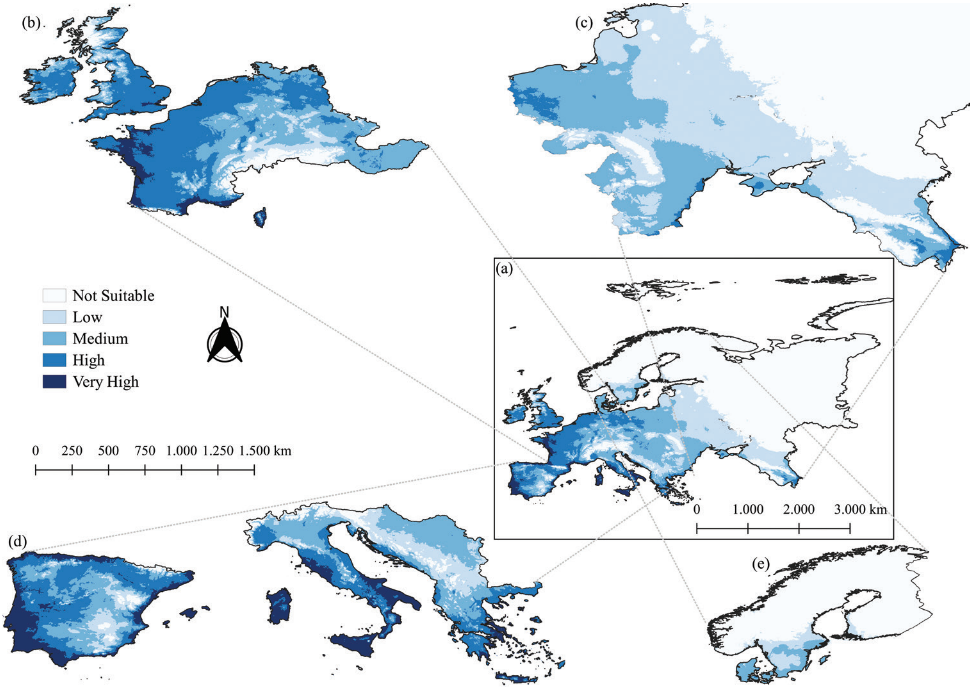

Figure 6. Climate suitability model of *Chrysomya albiceps* for the year 2050 in the least optimistic scenario (SSP5-8.5) in the Europe (**a**) and sub-regions Western (**b**), Eastern (**c**), Southern (**d**) and Northern (**e**). Model ran in Maxent and figure redrawn in ArcGIS software.

power (see Suppl. material 3, Fig. 1). Bio1 was found to be the most useful variable in explaining the potential distribution of *C. albiceps* worldwide in the work of Hosni et al. (2022). Bio11 (Mean Temperature of Coldest Quarter) was also identified as an important variable in this study. Similarly, these two variables were found to be the most important in explaining the potential future distribution of *Chrysomya bezziana* (Villeneuve, 1914) (Hosni et al. 2020). For other subtropical/tropical insects like *Aedes albopictus* (Skuse, 1894), which has recently colonized Europe, bio11 is considered to be the limiting variable for its potential distribution (Cunze et al. 2016). In contrast, bio15 (Precipitation Seasonality - Coefficient of Variation) has been identified as the best explanatory variable for the potential distribution of species in the family Syrphidae in Europe (Miličić et al. 2018; Milić et al. 2019).

Climate suitability in the tested models is also explained by bio7 (Temperature Annual Range), a variable related to seasonality (Fig. 2, Suppl. material 3). In subtropical regions, such as Portugal and Spain, the abundance of *C. albiceps* is seasonally dependent, increasing during the hottest periods of the year. The colder seasons limit the species, as its abundance decreases under such conditions (Prado e Castro et al. 2012).

In Fig. 9, the gains and losses in climate suitability can be seen, with most gains concentrated in eastern and northern Europe, while suitability losses are distributed

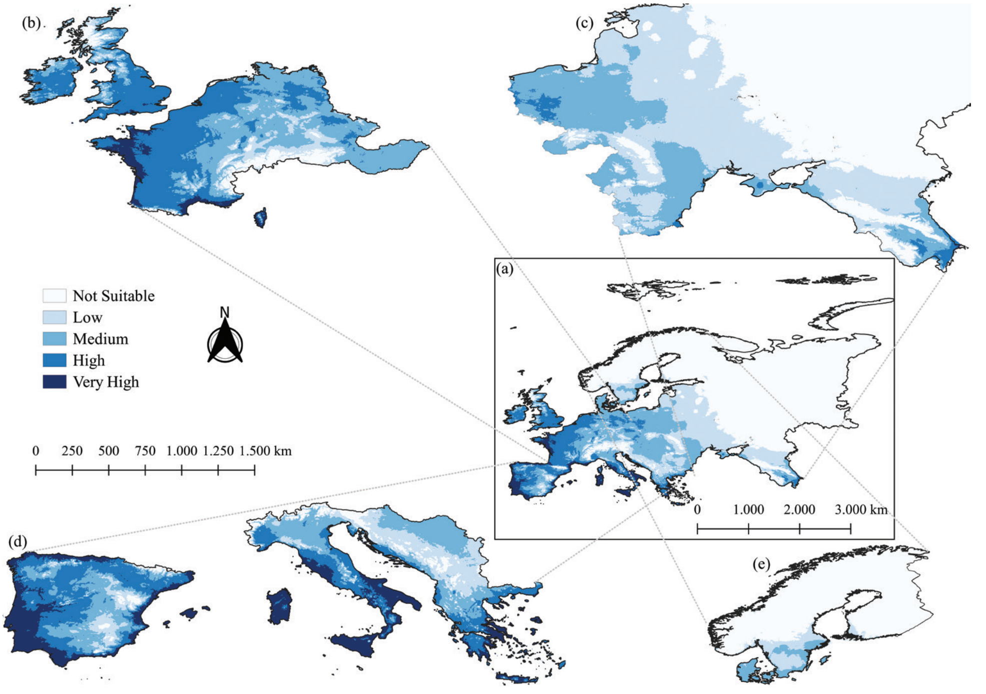

Figure 7. Climate suitability model of *Chrysomya albiceps* for the year 2070 in the most optimistic scenario (SSP1-2.6) in the Europe (**a**) and sub-regions Western (**b**), Eastern (**c**), Southern (**d**) and Northern (**e**). Model ran in Maxent and figure redrawn in ArcGIS software.

more evenly across the continent. These results are consistent with the predictions of the IPCC (2021), which anticipate the highest levels of global warming in northern and eastern Europe, as well as in northern Scandinavia and the interior areas of Mediterranean countries. The various future scenarios demonstrate that much of the areas remained unaltered (Fig. 9), including southern Europe, in contrast to the results of Hosni et al. (2022), who, when evaluating the potential distribution of *C. albiceps* worldwide, stated that the species would practically disappear from the same region. Southern Europe is one of the oldest regions where *C. albiceps* historically occurred (Holdaway 1933). Even though notable climate changes may occur in the region (IPCC 2021), it is unlikely that the species would stop occurring in these regions.

Chrysomya albiceps, being poikilothermic, has its development, physiology, and distribution greatly influenced by temperature (Marchenko 2001; Hosni et al. 2022). Therefore, it was expected that temperature would be the variable that would best explain its climate suitability in Europe. The mean annual temperature range for the species is between 9 °C and 27 °C, as noted by Hosni et al. (2022). The life cycle of the species has been studied under experimental conditions between 11 °C and 40 °C in various locations around the world (Queiroz and Milward-de-Azevedo 1991; Aguiar-Coelho and Milward-de-Azevedo 1995; Queiroz 1996; Marchenko 2001; Al-Misned et al. 2003; Kheirallah et al. 2007; Richards et al. 2009; Beuter and Mendes 2013;

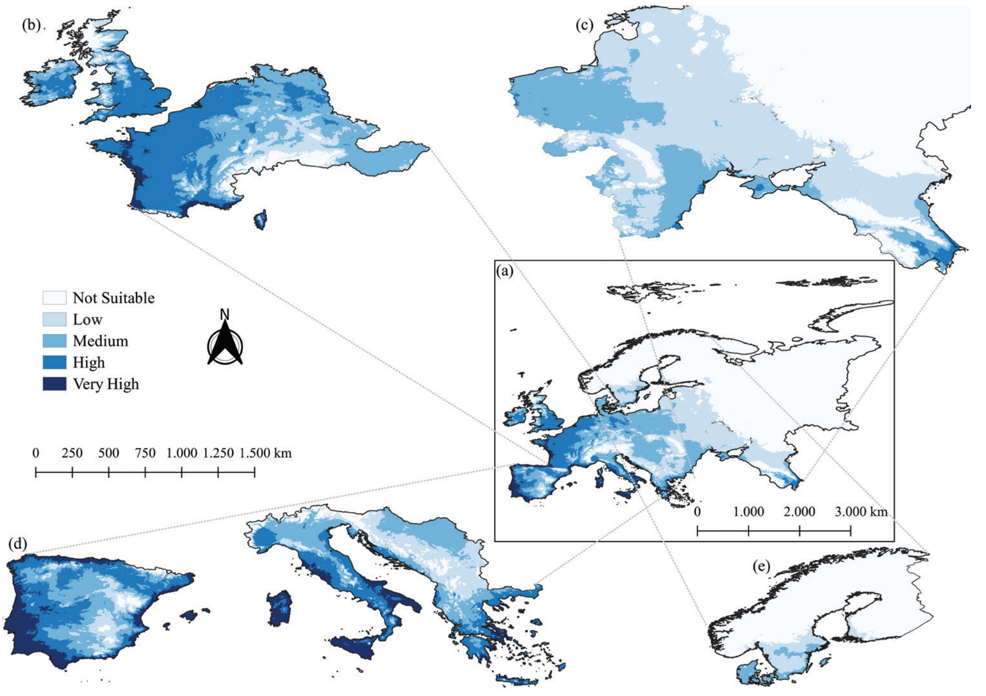

Figure 8. Climate suitability model of *Chrysomya albiceps* for the year 2070 under least optimistic scenario (SSP5-8.5) in the Europe (**a**) and sub-regions Western (**b**), Eastern (**c**), Southern (**d**) and Northern (**e**). Model ran in Maxent and figure redrawn in ArcGIS software.

Al-Shareef and Al-Qurashi 2016; Salimi et al. 2018; Kordshouli et al. 2021), including Europe (Grassberger et al. 2003). In this context, the development of the species is interrupted at the upper temperature threshold of 37 °C (Kordshouli et al. 2021), and at the lower temperature thresholds of 15 °C (Grassberger et al. 2003) and 13 °C (Marchenko 2001). Makovetskaya and Verves (2018) hypothesized that survival at these temperatures is sufficient for the species to spread to more sites in Europe, in addition to the Asian portions of southern Russia. Climate predictions suggest that the temperature in the old continent may increase from 1.2–3.4 °C to 4.1–8.5 °C in the coming years, in more and less optimistic scenarios (IPCC 2021). In this climate scenario, the hypothesis of Makovetskaya and Verves (2018) may be confirmed.

The models generated in this work can be used to help predict potential future distributions of *C. albiceps*. To better understand this species distribution around the world is an important contribution to Forensic Entomology. For instance, Turchetto and Vanin (2004) comment that the tropical species of forensic interest *Hermetia illucens* (Linnaeus, 1758) arrived in Italy in 1956, but only recently reached the colder areas of the country. This species is reported by the same authors as a superior competitor to the indigenous species. If conditions are suitable, *C. albiceps* can rapidly spread into new areas, changing the composition and dynamics of native blowfly communities, and consequently, the micro-ecosystems shaped by corpse decomposition (Baumgartner and Greenberg 1984;

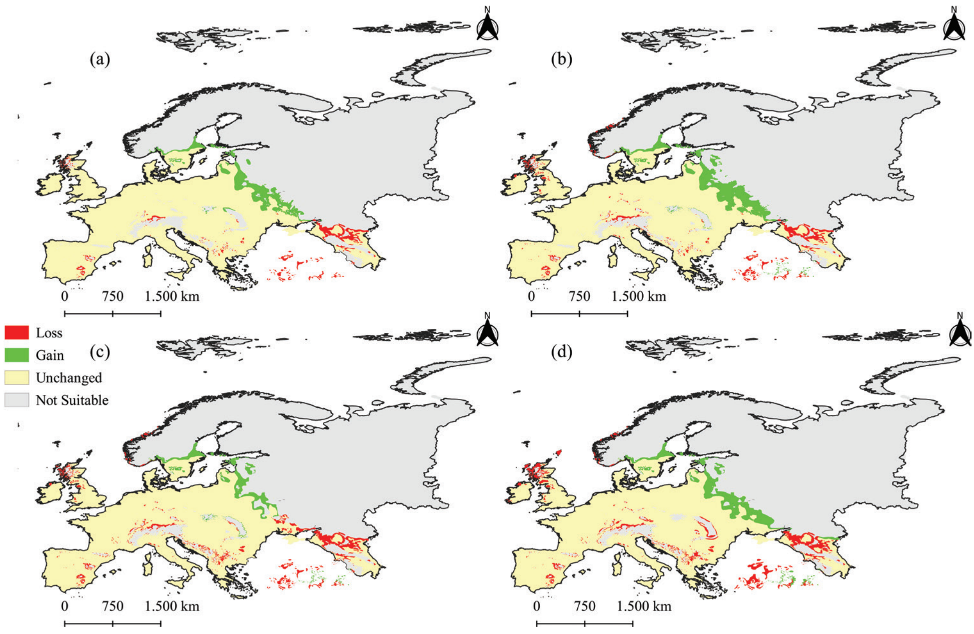

Figure 9. Variations in climate suitability in the 2050-SSP1-2.6 (**a**), 2050-SSP5-8.5 (**b**), 2070-SSP1-2.6 (**c**) and 2050-SSP5-8.5 (**d**) predictive scenarios. Gains (in km^2) from climate suitability were at a = 286.77, b = 451.67, c = 142.82 and d = 334.61. Losses (in km^2) from climate suitability were at a = 196.2, b = 257.19, c = 297.99, d = 383.78. Threshold > 0.4.

Braack and Retief 1986). This fly may be responsible for resetting the Post Mortem Interval due to its action on animal carcasses by preying on other species that may have arrived first (Grassberger et al. 2003). Since the beginning of the 21st century, *C. albiceps* is reported as a potential forensic species in Central Europe (Povolný 2002; Grassberger et al. 2003). Nonetheless, there are actual cases since 1995 where the species was recorded in Switzerland on the corpse of a man (Amendt et al. 2015). This indicates that the species already occurred sporadically in colder areas, but only really started to definitively colonize new areas a few years later. This periodic colonization is exemplified in Poland by Michalski and Szpila (2016). In addition, another reason not to neglect *C. albiceps* dispersal throughout Europe and neighboring countries is the report in Bulgaria of sheep myiasis, as well as in northern Morocco (Sotiraki and Hall 2012).

Conclusion

Annual Mean Temperature and Temperature Annual Range were the variables that contributed the most to the climate suitability model in the present work. From the model generated, it is concluded that much of Europe is climatically suitable for *C. albiceps*. In future scenarios, the suitability increases in northern and eastern Europe, with areas of gains concentrated in these locations, which appears to align with the recent geographical dispersion of the species across the continent. Meanwhile, losses of areas appear to be more evenly distributed. These changes in climate suitability may have implications for the potential future distribution of the species, which could colonize new areas in Europe depending on the climatic dynamics in the coming years. Being one of the most important species in the forensic field, besides being a potential myiasis agent, the dispersion of *C. albiceps* to new locations should not be neglected.

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Supplementary material 1

References acquired from the databases cited in the manuscript and consulted in the literature review to generate a dataset of geographic coordinates of the species *Chrysomya albiceps*

Authors: Sérgio José Menezes Rodrigues Filho, Fabrício dos Santos Lobato, Carlos Henrique Medeiros de Abreu, Maria Teresa Rebelo

Data type: List of references

Link: https://doi.org/10.3897/neobiota.85.96687.suppl1

Supplementary material 2

Occurrence points of *Chrysomya albiceps* recorded from the scientific literature and in the GBIF database

Authors: Sérgio José Menezes Rodrigues Filho, Fabrício dos Santos Lobato, Carlos Henrique Medeiros de Abreu, Maria Teresa Rebelo

Data type: Geographical coordinates

Link: https://doi.org/10.3897/neobiota.85.96687.suppl2

Supplementary material 3

Supplementary information

Authors: Sérgio José Menezes Rodrigues Filho, Fabrício dos Santos Lobato, Carlos Henrique Medeiros de Abreu, Maria Teresa Rebelo

Data type: table, figure and description

Explanation note: The file has a table and a figure and a description of bioclimatic variables. The description of the table is as follows: Results of the correlation between bioclimatic variables. Variables that correlated more than r > 0.7 were excluded. The variables chosen were 01, (Bio1, Annual Mean Temperature), 02 (Bio2, Mean Diurnal Range, mean of monthly max temp – min temp), 07 (Bio7, Annual Temperature Range), 12 (Bio12, Annual Precipitation) and 15 (Bio15, Precipitation Seasonality, Coefficient of Variation). The description of the figure is a follows: Results of the jackknife test of variable importance. This test is part of the output of the Maxent program.

Link: https://doi.org/10.3897/neobiota.85.96687.suppl3