



# European beewolf (*Philanthus triangulum*) will expand its geographic range as a result of climate warming

Piotr Olszewski<sup>1</sup> · Marcin K. Dyderski<sup>2</sup> · Łukasz Dylewski<sup>3</sup> · Petr Bogusch<sup>4</sup> · Christian Schmid-Egger<sup>5</sup> · Toshko Ljubomirov<sup>6</sup> · Dominique Zimmermann<sup>7</sup> · Romain Le Divelec<sup>8</sup> · Bogdan Wiśniowski<sup>9</sup> · Lucyna Twerd<sup>10</sup> · Tadeusz Pawlikowski<sup>11</sup> · Maurizio Mei<sup>12</sup> · Alexandra Florina Popa<sup>13,14</sup> · Jakub Szczypek<sup>11</sup> · Tim Sparks<sup>3</sup> · Radosław Puchałka<sup>11,15</sup>

Received: 23 April 2022 / Accepted: 10 October 2022 / Published online: 21 October 2022  
© The Author(s) 2022

## Abstract

Climate change is an important driver of the spread of apiary pests and honeybee predators. These impact on one of the economically most important pollinators and thus pose serious threats to the functioning of both natural ecosystems and crops. We investigated the impact of the predicted climate change in the periods 2040–2060 and 2060–2080 on the potential distribution of the European beewolf *Philanthus triangulum*, a specialized honeybee predator. We modelled its potential distribution using the MaxEnt method based on contemporary occurrence data and bioclimatic variables. Our model had an overall good performance (AUC = 0.864) and the threshold of occurrence probability, assessed as the point with the highest sum of sensitivity and specificity, was at 0.533. Annual temperature range (69.5%), mean temperature in the warmest quarter (12.4%), and precipitation in the warmest quarter (7.9%) were the principal bioclimatic variables significantly affecting the potential distribution of the European beewolf. We predicted the potential distribution shifts within two scenarios (optimistic RPC4.5 and pessimistic RCP8.5) and three Global Circulation Models (HadGEM2-ES, IPSL-CM5A-LR, and MPI-SM-LR). Both optimistic and pessimistic scenarios showed that climate change will significantly increase the availability of European beewolf potential niches. Losses of potential niches will only affect small areas in southern Europe. Most of the anticipated changes for the period 2060–2080 will already have occurred in 2040–2060. The predicted range expansion of European beewolf suggests that occurrence and abundance of this species should be monitored.

**Keywords** Beekeeping · Beewolf · Honeybee predation · Insect pest · MaxEnt · Species distribution models

## Introduction

The progressive increase in the human population, as well as human-mediated activities, e.g., land-use change due to an expansion of agriculture (Laurance et al. 2013), habitat degradation (Kerr and Deguise 2004), invasion of alien species (Clavero and García-Berthou 2005), and plastic pollution (Chae and An 2018), have negative consequences on species survival and ecosystem functioning worldwide (Pereira et al. 2010). However, one of the most significant global biodiversity threats is climate change (Sala et al. 2000).

Climate change alters the key abiotic agents of selection, i.e., CO<sub>2</sub>, temperature, and precipitation (Arias et al. 2021), transforming current ecosystems and food webs (Schmitz et al. 2003; Alava et al. 2017; Bartley et al. 2019; Pound et al. 2020). It may affect species range shifts, leading to a spatial mismatch between organisms and decoupling their interactions (Nakazawa and Doi 2012; Miller-Struttman et al. 2015; Damien and Tougeron 2019). Climate change may directly or indirectly influence plant and animal species distribution shifts (Travis et al. 2013). Understanding the effect of future climate change on biodiversity is important not only in conservation biology (Tam and McDaniels 2013), but also for human health and wellbeing (Jones et al. 2012; McMichael 2013), and the global economy (Newell and Paterson 2010). Projected range expansion of insect pests (Battisti and Larsson 2015), vectors of human diseases (Bueno

---

Communicated by Wolfgang Cramer

✉ Radosław Puchałka  
puchalka@umk.pl

Extended author information available on the last page of the article

Marí and Jiménez-Peydró 2013), and invasive alien species (Anibaba et al. 2022) are prime examples of this importance.

Insects are sensitive to increased temperature (Beck 1983), and consequently to the effects of global climate change (Halsch et al. 2021). Global warming affects insect ecology, physiology, and behavior (Pelini et al. 2009) and causes mismatches in their trophic mutualistic and antagonistic interactions with plants and other animals (Blois et al. 2013). Due to rapid climate change, several life-history traits such as survival and growth rate are likely to change (Bale et al. 2002). This might also alter the population size and temporal and spatial dynamics of insect communities (Pelini et al. 2009; Raven and Wagner 2021) and cause shifts in their ranges (Arribas et al. 2012; Hill et al. 2017; Martín-Vélez and Abellán 2022).

Global warming is also linked with changing predator–prey interactions (Laws 2017). Changes in local community composition over space and time due to shifting species ranges or the creation of novel communities may have consequences in population dynamics for both predator and prey. This may affect ecosystems in many ways, as seen with the predator effect on pollination — plant interactions (Damien and Tougeron 2019). Several studies have shown that predators can be a major source of mortality of pollinators, decreasing pollinator population size as well as reducing the pollination effectiveness on seed set by reducing the density of pollinators (Dukas 2001a, b, 2004; Dukas and Morse 2003; Muñoz and Arroyo 2004; Jones and Dornhaus 2011). Understanding how climate change will contribute to the range expansion of predators could help prevent the local extinction of pollinator communities.

Evidence suggests that climatic changes will significantly, and in some cases irreversibly, harm the economy and many ecosystems alike (Willett et al. 2010). Widely available maps of current and future climatic conditions and the rapidly increasing number of species observations in scientific and citizen science databases allow for increasingly extensive studies of spatio-temporal changes in species distributions (Puchałka et al. 2021, 2022). Species distribution modeling is a widely used tool for predicting potential changes in the distribution range of plant and animal species and detecting niche shifts with climate change (Guisan and Thuiller 2005; Hill et al. 2017; Dyderski et al. 2018). Recent studies of the effect of climate change on future species distribution have focused on native and on potentially invasive alien insect pests in agriculture and forest ecosystems (Hlásny and Turcáni 2009; Cudmore et al. 2010; Qin et al. 2019). Future projections suggest a northwards range expansion of pest insect species in the Northern Hemisphere and southwards in the Southern Hemisphere, where a more suitable niche will be available (Qin et al. 2019; Cornelissen et al. 2019; Ramasamy et al. 2022). For example, Cornelissen et al. (2019) predicted that the distribution of *Aethina*

*tumida*, an invasive pest of the honeybee endemic to sub-Saharan Africa, will expand into the Northern Hemisphere and potentially become a global threat. In contrast, one of the most important insect groups, pollinators, that provide an ecosystem service for the human food production sector, seems to be mostly negatively affected by climatic warming (Potts et al. 2010; Goulson et al. 2015; Imbach et al. 2017).

Climate change may increase the expansion of invasive pest species and diseases as well as having negative consequences on behavior and physiology that may lead to diversity loss in bees (Potts et al. 2010; Polce et al. 2014; Cornelissen et al. 2019; Carrasco et al. 2020; Martínez López et al. 2021). However, knowledge of the potential effect of climate change on bee predators, such as digger wasps (e.g., *Philanthus* spp.), is currently lacking (but see Eid and Abou-Shaara 2021).

The European beewolf *Philanthus triangulum* (Philanthidae) is a medium-sized digger wasp (female 13–17 mm, male 8–10 mm in length), whose distribution stretches from the Atlantic coast of Europe to the Middle East and from Scandinavia in the north to South Africa in the south (Bitsch et al. 1997; Blösch 2000; Pulawski 2021; Sann et al. 2018). In Europe, both males and females are active from mid-June to October. Males usually appear a week before females and stay at the edge of the breeding sites. Females choose sandy sites for their nests (in both horizontal and vertical surfaces) and dig their burrows using their legs and mandibles. Adult European beewolves feed on pollen and nectar from flowers but can also obtain nectar and pollen by squeezing them from the bodies of their prey (Blösch 2000). The food of the larvae consists of bees usually attacked at flowers, but they may also be taken in flight. The prey is paralyzed by being stung, always behind the first pair of legs (Rathmayer 1962). European beewolf is generally considered to be economically harmful because it mainly hunts honeybees (*Apis mellifera*). Tinbergen (1958) showed that an aggregation of European beewolf can capture several thousand honeybees per day. Simonthomas and Simonthomas (1980) concluded that an aggregation of 3000 European beewolf individuals, captured up to 30,000 honeybees per day. The number of burrows in nest aggregations can be up to 15,000 (Else 1995a, b). This observation was confirmed for another bee wolf species, *Philanthus bicinctus*, in northwest Wyoming, USA, where it was estimated that the wasp aggregation captured several hundred to a few thousand bumblebees per day (Dukas 2004). Hamm and Richards (1930) reported that European beewolf can also hunt solitary bees, e.g., *Andrena flavipes* or *Lasioglossum zonulum* (Smith 1858; Fahringer 1922). Some studies have shown that this species can locally affect beekeeping due to their use of honeybees as larval food (El-Borollosy et al. 1973; Simonthomas and Simonthomas 1980; Petrov 1996). The European beewolf can also impact populations of wild bees and other pollinators, especially where few honeybees are present (Blösch 2000). It is conceivable

that the European beewolf may become a serious threat for the honeybees in areas where it was not previously present.

The distribution of European beewolf is susceptible to climatic fluctuations, e.g., temperature (Braestrup and Nielsen 1941; Hansen 1997). The entire population of this species may decline due to long-term adverse weather conditions (Blösch 2000). The European beewolf is distributed mainly in the mid latitudes and the tropics. Hence, we hypothesized that this species may benefit from predicted climate change and, in the future, could become a potential threat for honeybees in Europe. In this study, we aimed to determine the impact of climate change in the 2040–2060 and 2060–2080 periods on the potential distribution of the European beewolf, a specialized predator of bees.

## Materials and methods

### European beewolf occurrence data

The occurrences of European beewolf (Supplementary material, Fig. 1) were obtained from scientific papers, Global Biodiversity Information Facility ([www.gbif.org](http://www.gbif.org)) and confirmed identifications of georeferenced photographs on the webpage Biodiversidad Virtual ([www.biodiversidadvirtual.org](http://www.biodiversidadvirtual.org)). The gaps in occurrence data were filled by the authors' unpublished field observations. In total, we obtained 10,574 distribution records with associated geographical coordinates (latitude and longitude), which were loaded into a spatially referenced database. Among all records, 53.6% were collected after 2015, 84.4% after 2005, and 92.9% after 1990. To overcome any disadvantage of citizen science data collection resulting in uneven sampling that could affect analyses, we randomly selected a single record from each 0.25° grid raster cell for MaxEnt analysis (Rocchini and Garzon-Lopez 2017). This resulted in 1021 single observations to model current and future potential distribution of European beewolf.

### Climatic data — predictors of the potential distribution of the European beewolf

We obtained 19 bioclimatic variables (Table 1) (2.5' resolution) (Booth 2018) from the WorldClim 1.4 database ([www.worldclim.org](http://www.worldclim.org)); (Hijmans et al. 2005). These data on annual, monthly, and/or seasonal temperature and rainfall indices are commonly used in modeling potential geographical ranges (Booth et al. 2014; Booth 2018) and are the factors considered to restrict the geographic distribution of species (Pearson and Dawson 2003; O'Donnell and Ignizio 2012; Sullivan 2014). To limit the number of variables and to avoid collinearity, we assessed the correlation matrix of climatic data for European beewolf occurrences. Then, from each

**Table 1** Bioclimatic variables used in the potential distribution modelling of *Philanthus triangulum*. The finally used in the analysis maps were marked with asterisks

Bioclimatic variables	Abbreviation
Annual mean temperature	bio1
Mean monthly temperature range	bio2*
Isothermality ((BIO2/BIO7) × 100)	bio3
Temperature seasonality (STD × 100)	bio4
Max temperature of warmest month	bio5
Min temperature of coldest month	bio6
Temperature annual range (5–6)	bio7
Mean temperature of wettest quarter	bio8*
Mean temperature of driest quarter	bio9
Mean temperature of warmest quarter	bio10*
Mean temperature of coldest quarter	bio11*
Annual precipitation	bio12
Precipitation of wettest month	bio13
Precipitation of driest month	bio14
Precipitation seasonality (CV– Coefficient of Variation)	bio15*
Precipitation of wettest quarter	bio16*
Precipitation of driest quarter	bio17
Precipitation of warmest quarter	bio18*
Precipitation of coldest quarter	bio19*

pair of variables containing similar information (e.g., bio5 and bio10, or bio6 and bio11), we removed the one with  $|r| > 0.7$  (Puchałka et al. 2021). Taking into account information about the studied biology of the species, we can justify the choice of climate variables as follows. Bio2, 3, 7, and 10 are variables that preface the amplitude of daily, seasonal, and annual temperature ranges, which may be important to the survival of populations of this Mediterranean species, which may be affected by temperature decreases (Braestrup and Nielsen 1941; Leclercq 1944). Bio17 may determine population survival because snow cover in colder regions can protect nests from low temperatures. Meanwhile, bio18 and 19 inform on the amount of precipitation during Europe's warmest and wettest period of the year, which falls in summer, the period of imago activity (Simonthomas and Poorter 1972). This reduced the dataset to seven variables for modeling the potential distribution of European beewolf (Table 1).

### Potential distribution modeling

We used the MaxEnt model to model the potential distribution of European beewolf. This is the presence-only method, which uses point occurrence data and pseudoabsences (Phillips et al. 2006; Elith et al. 2011). In contrast to parametric models and other classification tools, MaxEnt can work without true absence data in the theoretical assumptions, but instead,

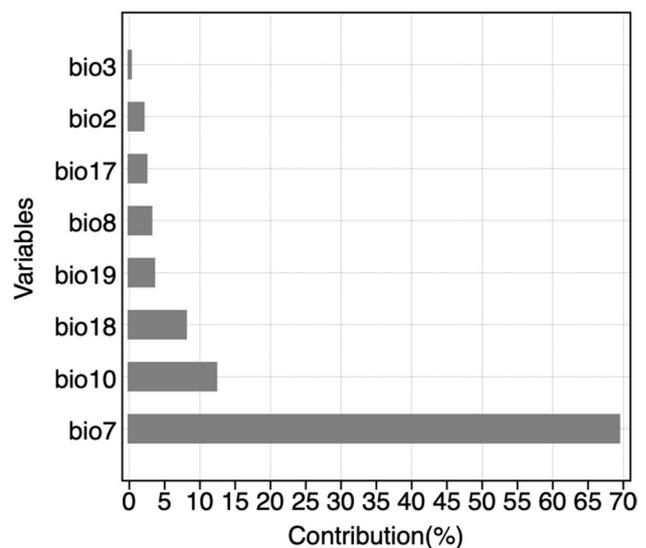
it uses background data (so-called pseudoabsences). As MaxEnt analyzes patterns of presences distinct from the background data, the prevalence of background points makes the model more conservative, requiring a stronger signal than would be the case for equal proportions of presences and pseudoabsences (Elith et al. 2011). Prior to analyses, we split the dataset into a training set (80% of observations) used for model development, and an independent validation set (20% of observations). This split allowed us to prevent overfitting when validating the model using the training set. We used default MaxEnt settings with 10,000 randomly selected pseudoabsence points. We assessed model quality using area under receiver operator curve (AUC) as a metric depending on true positive and true negative rates (i.e., rates of positive and negative overlapping the real and predicted occurrences). The output of the MaxEnt model is a measure of climatic suitability for studied species in a particular raster cell. To obtain presence-absence information, we calculated the threshold — the probability value with the highest sum of the sensitivity (true positive rate) and specificity (true negative rate). Such an approach balances false negatives and false positives (Fielding and Bell 1997). MaxEnt also returns variable importance, expressed as percentage contribution to the model. We used *dismo* package (Hijmans et al. 2020) for MaxEnt model development and *raster* (Hijmans 2020) and *sf* (Pebesma 2018) packages for spatial data processing.

We developed a prediction of the species range shifts for two time horizons: 2040–2060 (hereafter 2050) and 2060–2080 (hereafter 2070). Models were created for two scenarios of increasing climate change magnitude, reflected in the 5th Assessment Report of IPCC by the respective representative concentration pathways (RCPs), based on the difference between the pre-industrial level of radiative forcing (in  $W\ m^{-2}$ ) and that predicted for the year 2100 (van Vuuren et al. 2011; Harris et al. 2014; IPCC 2014). The more optimistic variant (RCP4.5) predicts an increase in  $CO_2$  concentration in the atmosphere to 650 ppm and an average temperature increase of 1.0–2.6 °C by 2100. This is a scenario predicting intensive economic growth, but assuming emission reduction. The pessimistic scenario (RCP8.5) assumes a  $CO_2$  concentration of 1350 ppm and an average temperature increase of 2.6–4.8 °C by 2100 — this is a scenario of intensive economic growth with intensive use of fossil fuels (van Vuuren et al. 2011; Harris et al. 2014; IPCC 2014). To account for uncertainty across different global circulation models (GCMs) used in predicting future values of bioclimatic variables (Thuiller et al. 2019; Paż-Dyderska et al. 2021), we used three GCMs and averaged the output to provide a more robust forecasts of range shifts. The three GCMs were — HadGEM2-ES (Jones et al. 2011), IPSL-CM5A-LR (Dufresne et al. 2013), and MPI-SM-LR (Giorgetta et al. 2013), reflecting, respectively, low,

moderate, and high levels of change in climate conditions depending on scenarios of  $CO_2$  concentration (Goberville et al. 2015). The uncertainty of predictions was estimated using standard deviation (SD) among GCMs for RCPs (see Supplementary material).

## Results

Our model showed an overall good performance, expressed by a high AUC (0.864) assessed using a validation dataset. The threshold of occurrence probability, assessed as the point with the highest sum of sensitivity and specificity, was at 0.533. The most important bioclimatic factors influencing the occurrence of European beewolf were “annual temperature range” (bio7), “mean temperature of the warmest quarter” (bio10), and “precipitation of the warmest quarter” (bio18) with importance > 5%; all other variables had importance < 5% (Fig. 1). The probability of European beewolf occurrence decreases with increased annual temperature range (bio7) and drops with increase of precipitation of the warmest quarter (bio18). When it comes to mean temperature of warmest quarter (bio10), it seems that below some threshold value, the probability of European beewolf occurrence is negligible. Above this threshold is a narrow margin of optimum conditions above which probability of occurrence again slowly decreases



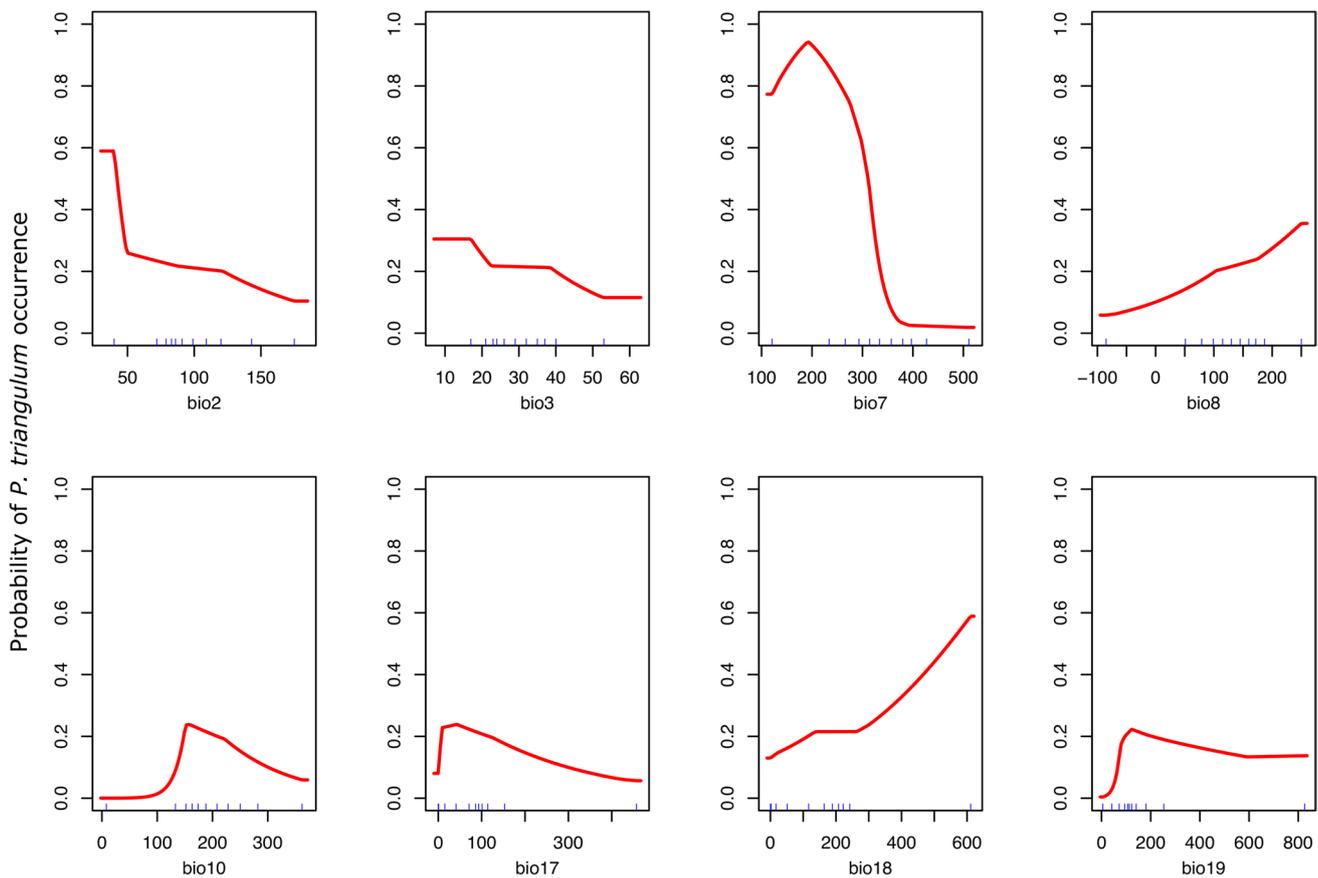
**Fig. 1** Variable importance, expressed as its contribution to the MaxEnt model. Explanations: bio2, mean monthly temperature range; bio8, mean temperature of wettest quarter; bio10, mean temperature of warmest quarter; bio11, mean temperature of coldest quarter; bio15, precipitation seasonality (CV, coefficient of variation); bio16, precipitation of wettest quarter; bio18, precipitation of warmest quarter; bio19, precipitation of coldest quarter

(Fig. 2). All GCMs variants analyzed in the context of each RCP indicate that the European beewolf will gain more climatically optimal areas for colonization than it will lose (Fig. 3), suggesting that it may become a more significant bee predator in the coming decades. Uncertainty of predictions among GCMs, expressed by the SD, was highest in Eastern Europe and ranged from <0.001 to 0.538, with medians of 0.044, 0.054, 0.063, and 0.089 for 2050 RCP 4.5, 2050 RCP 8.5, 2070 RCP 4.5, and 2070 RCP 8.5 (Supplementary material, Fig. 2).

The climatically suitable areas cover almost all of Europe, except for high mountain ranges, reach the southern and coastal borders of Finland, Sweden, and Norway, southern parts of the British Isles, westwards to the Coastal regions of Portugal, and in the south to the Greek islands. As predicted by the model, this latter area will become increasingly unsuitable (Fig. 4). Regardless of the accepted scenario, the areas potentially suitable for occupation by European beewolf in the north-eastern part of the Iberian Peninsula will be significantly reduced. According to the fitted model, the species will also lose climatically suitable areas from the

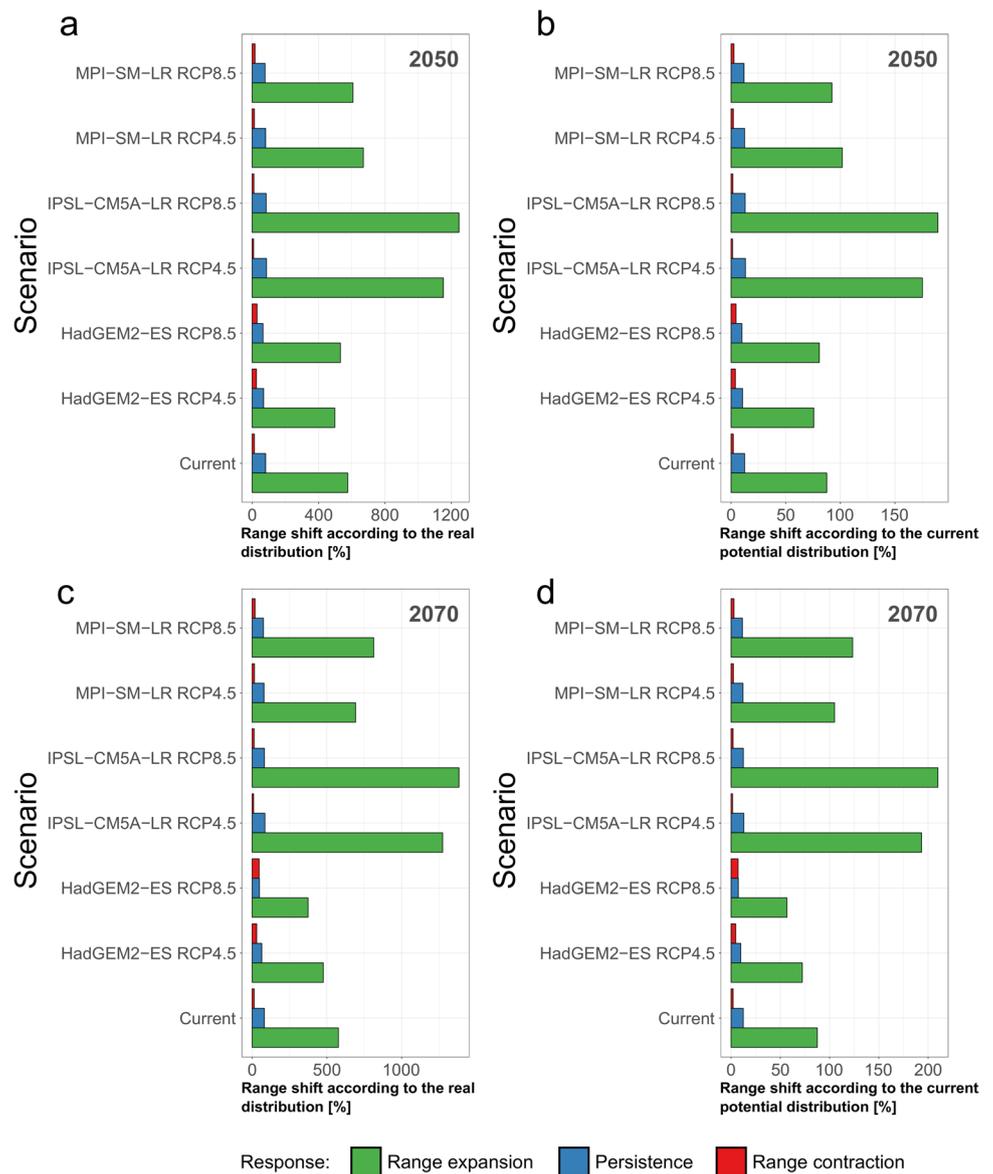
central part of the peninsula where it already occurs in sub-optimal environments. A similar situation will apply to the southern part of France and to northern and central Italy. However, the greatest loss of climatically suitable habitats for European beewolf will be in south-eastern Europe, from the Adriatic Sea coast to the Black Sea coast.

Averaged forecasts for the pessimistic scenario (RCP8.5) suggest that by 2070, following the loss of climatically suitable habitats (range contraction) in the southern part of Europe below 46°N, the European beewolf will remain only in areas relatively close to the shores of large water bodies. In the north, we predicted range expansion, especially in the British Isles, Scandinavian Peninsula, and from the Kola Peninsula as far east as Moscow and Novaya Zemlya. However, the scale of the predicted loss of climatically suitable habitats from southern Europe is small compared to the expected expansion towards the north. Even in the optimistic variant to 2050, the climatically suitable areas for European beewolf will extend beyond the Arctic Circle as far as the northern part of the Kola Peninsula. The habitat conditions for European beewolf will quickly become more



**Fig. 2** Marginal responses of *Philanthus triangulum* climatic suitability to particular bioclimatic variables (see Table 1 for abbreviations). The red line indicates the predicted response while rugs at the bottom of each panel reflect the distribution of each bioclimatic variable

**Fig. 3** Percentage distribution range shift predicted for six climate change scenarios for three global circulation models and two time-horizons: 2050 (a and b) and 2070 (c and d), related to the current real distribution (number of currently occupied grid cells; a and c), and related to the current potential (predicted) distribution (b and d)



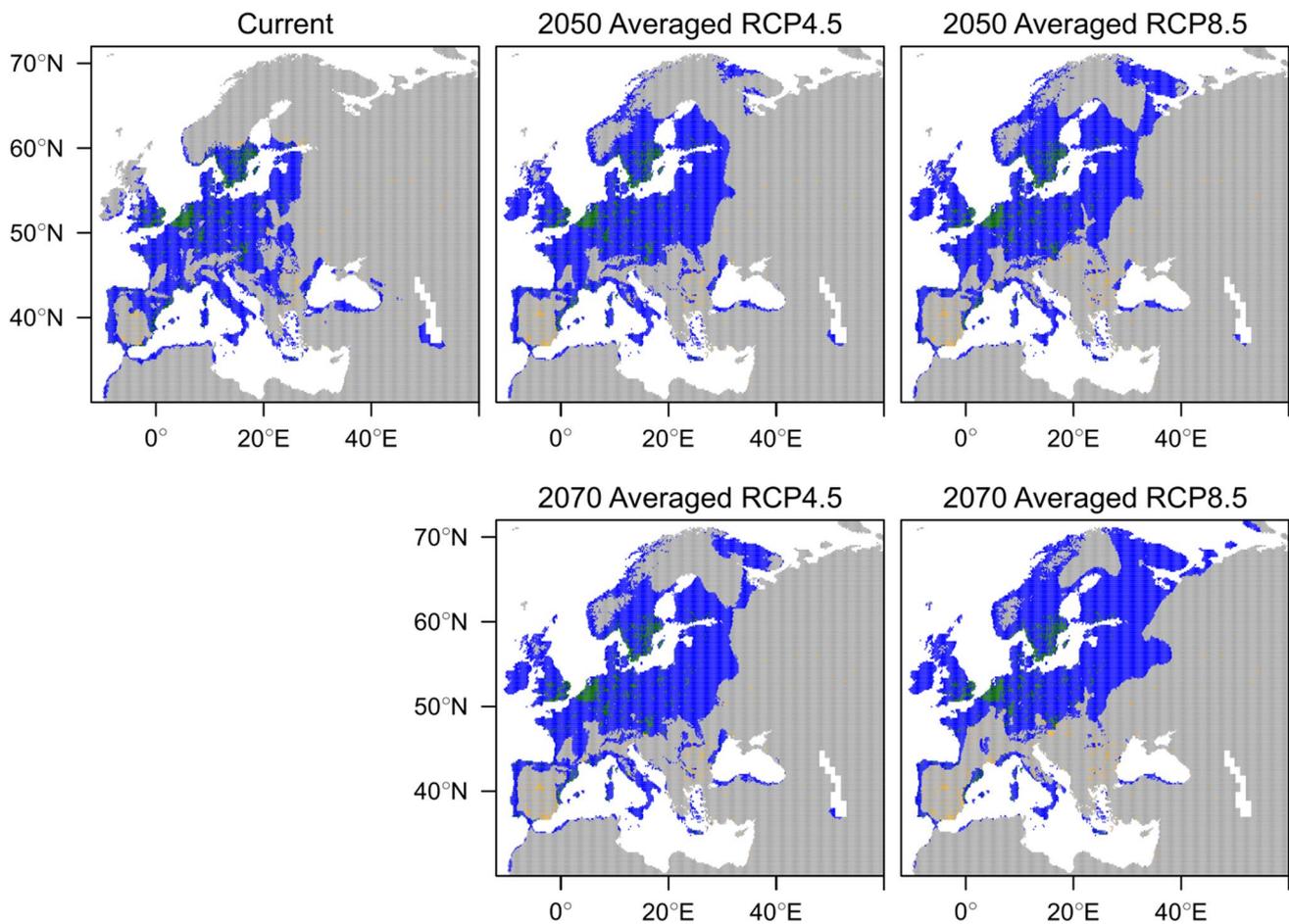
climatically suitable in the south of Finland and the central part of Sweden. These areas will be within the optimum zone of European beewolf habitat requirements by 2050, regardless of the accepted scenario. The situation will be slightly different in Norway, where optimal conditions are forecasted mainly along the coast up to  $\sim 70^{\circ}\text{N}$ . In the western part of Europe, changes in habitat conditions will expose Ireland and Scotland, which currently do not have conditions climatically suitable for European beewolf, to rapid colonization by 2050 in each analyzed scenario.

In the forecasts for both 2050 and 2070, all variants assume the expansion of the species range, especially towards the north. In 2050, two GCMs under the pessimistic scenario predict a greater expansion than in the optimistic scenario, while the MPI-SM-LR GCM shows similar values. Regardless of the baseline point of reference (either the actual or

potential current distribution), the projections in both scenarios (pessimistic and optimistic) in 2050 and 2070 are similar (Fig. 3). Estimates based on the graphs indicate that the climatically suitable areas for European beewolf compared to today will increase by c. 50% by 2050 and by c. 100% by 2070. It also appears that the distribution of European beewolf will increase substantially compared to the current situation (only the HadGEM2-ES model predicts a slight reduction in the frequency of occurrence in all variants).

## Discussion

Here, we present the first study to assess the impact of global warming on a specialized predator of the honeybee on a European scale. Our projections predicted by various



**Fig. 4** Current and averaged projected ranges of *Philanthus triangulum* for two climate change scenarios: optimistic (RCP4.5) and pessimistic (RCP8.5) for 2050 and 2070, respectively. Green area: current

and future projected ranges; blue: potential expansion range; orange: potential range contraction; gray: climatically unsuitable in all climatic scenarios. Spatial resolution: 2.50 degrees

climatic scenarios suggest that the range of the European beewolf in the 2050 and 2070 scenarios will shift to the north-east. A similar pattern has been found in studies of other plant and animal species occurring in Europe (Dyderski et al. 2018; Iannella et al. 2020; Puchałka et al. 2021; Brygadyrenko et al. 2021).

Our future climatic predictions suggest that European beewolf will increase its distribution range to the north with simultaneous population reduction from the Mediterranean region, where the climatic conditions will be unsuitable for many insect species (e.g., Menéndez 2007; Vanhanen et al. 2007; Sánchez-Guillén et al. 2013). Based on previous empirical observations, European beewolf has increased its range since 1930, which might be a result of climatic changes (Leclercq 1960, 1973). The expansion of the European beewolf was recorded in the Scandinavia in 1942–1962 (Erlandsson 1962), and in North-West Germany in 1940–1977 (Haesler 1977). In the UK, the European beewolf was extremely rare. However, since 1980, the population there has expanded

dramatically, occurring now in southern and mid-northern Britain (Bantock 2010). Moreover, in Sweden and Denmark, the European beewolf was more abundant in 1940 than in previous years, possibly due to the relatively high summer temperatures of 1937–1939 (Braestrup and Nielsen 1941). In the Netherlands, Koster (1985) reported that the European beewolf was more common in 1979–1984 than in 1971. European beewolf is a rather Mediterranean species (Leclercq 1944), and it seems that the milder winters, which are a result of global warming, favor the northward spread of this species. A substantial part of the predicted changes in the European distribution of the European beewolf will be its expansion, mainly in a north-easterly direction. In Western Europe, the expansion of suitable area will cover nearly the entire British Isles (Fig. 4). A slightly different situation will occur in the south and in the center of Europe, where certain areas will be outside of the optimum habitat requirements of the species. This mainly concerns the central part of the Iberian Peninsula and the mountain ranges of central Europe.

Model predictions suggest that the most important bioclimatic variable determining the suitability of an area for the European beewolf was seasonal temperature range (Figs. 1 and 2). Temperature plays an essential role in the life of the European beewolf because it correlates with the availability of honeybees and hence the number of prey available to provision their nest. It can also prevent microbial spoilage of their food supplies in the ground (Strohm and Linsenmair 1997; Engl et al. 2016). Climate warming may have a substantial positive impact on the European beewolf potential niche availability and thus directly affect its abundance which, in turn, will contribute to the spread to the north and northeast of Europe. The future global warming scenarios project a rapid increase in climatic suitability for insect pests, especially in the Northern Hemisphere (Barbet-Massin et al. 2013; Hill et al. 2017; Qin et al. 2019). Thus, thermal climatic conditions play an important role in range shifts and in physiological adaptation for development (Vannote and Sweeney 1980) and survival (Kaiser et al. 2016; Maebe et al. 2021). Consequently, it has an impact on abundance and population size of insect pest species undergoing poleward range expansion due to warming (Økland et al. 2019; Qin et al. 2019; Cornelissen et al. 2019).

Currently, *Philanthus* spp. are of marginal concern to the beekeeping industry. However, empirical evidence suggests that aggregations of *Philanthus* species can capture from a hundred up to a thousand individuals of honeybee or other bee species per day (Tinbergen 1958; Simonthomas and Simonthomas 1980; Dukas 2004). Previous evidence suggests that novel predation by invasive wasps affects the mortality of native bee and domestic honeybee (Monceau et al. 2013; Hanna and Eason 2013). Although the European beewolf is currently a minor predator of bees, Cresswell (2017) estimated that rare predators with low prey-capture rates can significantly affect pollinator populations. He projected that 47% of bumblebee workers will be killed by spiders at a 1% chance of being caught. If the European beewolf increases its distribution range, it could exert strong top-down control on bee populations in the future. Until now, high densities of the European beewolf (Simonthomas and Simonthomas 1980; Else 1995a, b) were considered to be rather a local phenomenon. However, attention should be paid to the plasticity of nesting preferences of the European beewolf. Colonies of this species have been documented on moors (Falk 2010), dunes (Saure 2020), in coal ash and dust, in dumps from coal mines (Smit and de Boer 2008), and even in post-industrial sodium carbonate landfills (Twerd et al. 2017). The species has also become more frequently found in city centers (Burger 2007). Our study, predicting range expansion of European beewolf, is in line with studies predicting range expansion of other honeybee pests (Cornelissen et al. 2019; Giliba et al. 2020). Together with models predicting the decline of suitable niche for bee species (Potts et al. 2010; Goulson et al. 2015;

Imbach et al. 2017), climate change can therefore adversely affect both future global bee diversity and the beekeeping industry.

The factors determining the the threat posed by the presence of the European beewolf may be the local abundance of its population in a given area (Petrov 1996) and possible disturbances (e.g., increasing pressure on *A. mellifera*) in the relative proportions of predator and prey populations. Our results showed that climate change might lead to expansion of the European beewolf in Europe. Therefore, further studies on the phenology of the European beewolf (e.g., the number of generations per season) can better help understand the potential impact of this predator on honeybee survival and the beekeeping industry.

## Conclusions

In summary, our findings highlight that a honeybee predator, the European beewolf, may be affected by climate warming to expand its range to a potential new niche in the north and north-east of Europe. Therefore, there is a risk that the species will become widespread there and may put an additional burden on honeybee colonies and endanger the productivity of apiaries. By causing shifts in species niches and their phenology, climate change could lead to significant and, as yet, underestimated changes in community structure and interspecies interactions. Hence, it cannot be ruled out that the European beewolf, whose substantial negative effects on honeybees to date have only been described as local, may become a more significant pest of apiaries in the future. Therefore, we believe that further research is needed to better understand the ecology and population dynamics of this species, and to estimate whether a monitoring of its occurrence and abundance is needed.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10113-022-01987-z>.

**Acknowledgements** We would like to thank Eduardas Budrys, Leopoldo Castro, Alexander V. Martynov and Alexander Shlyakhtenok for sharing the occurrence data of *P. triangulum*.

**Funding** The research work of RP was done within the Research University – Initiative of Excellence: The Emerging Field “Global Environmental Changes” at Nicolaus Copernicus University in Toruń. The study was partially supported by the Institute of Dendrology of the Polish Academy of Sciences and by the Foundation for Polish Science (FNP). MKD acknowledges support from the Foundation for Polish Science (FNP) from the START scholarship.

**Data availability** The research was performed based on a data set obtained from the Global Biodiversity Information Facility (GBIF) database (<https://doi.org/10.15468/dl.27nf7g>) supplemented by occurrence data from the webpage Biodiversidad Virtual ([www.biodiversidadvirtual.org](http://www.biodiversidadvirtual.org)). The gaps in occurrence data were filled with the author’s unpublished data. This dataset is available from the first author (P) on reasonable request.

## Declarations

**Conflict of interest** The authors declare no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Alava JJ, Cheung WL, Ross PS, Rashid Sumaila R (2017) Climate change-contaminant interactions in marine food webs: toward a conceptual framework. *Glob Chang Biol* 23:3984–4001. <https://doi.org/10.1111/gcb.13667>
- Anibaba QA, Dyderski MK, Jagodziński AM (2022) Predicted range shifts of invasive giant hogweed (*Heracleum mantegazzianum*) in Europe. *Sci Total Environ* 825:154053. <https://doi.org/10.1016/j.scitotenv.2022.154053>
- Arias PA, Bellouin N, Coppola E, Jones RG, Krinner G et al (2021) Technical summary. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C et al (eds) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 33–144. <https://doi.org/10.1017/9781009157896.002>
- Arribas P, Abellán P, Velasco J, Bilton DT, Millán A et al (2012) Evaluating drivers of vulnerability to climate change: a guide for insect conservation strategies. *Glob Chang Biol* 18:2135–2146. <https://doi.org/10.1111/j.1365-2486.2012.02691.x>
- Bale JS, Masters GJ, Hodkinson ID, Awmack C, Bezemer TM et al (2002) Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. *Glob Chang Biol* 8:1–16. <https://doi.org/10.1046/j.1365-2486.2002.00451.x>
- Bantock T (2010) Information sheet the bee-wolf (*Philanthus triangulum*). Information Sheet 20. HYMETTUS and BWARS [http://hymettus.org.uk/downloads/Info\\_sheets\\_2010/20\\_Philanthus\\_triangulum\\_Icol\\_infosheet.pdf](http://hymettus.org.uk/downloads/Info_sheets_2010/20_Philanthus_triangulum_Icol_infosheet.pdf). Accessed 30 September 2022
- Barbet-Massin M, Rome Q, Muller F, Perrard A, Villemant C et al (2013) Climate change increases the risk of invasion by the Yellow-legged hornet. *Biol Conserv* 157:4–10. <https://doi.org/10.1016/j.biocon.2012.09.015>
- Bartley TJ, McCann KS, Bieg C, Cazelles K, Granados M et al (2019) Food web rewiring in a changing world. *Nat Ecol Evol* 3:1. <https://doi.org/10.1038/s41559-018-0772-3>
- Battisti A, Larsson S (2015) Climate change and insect pest distribution range. Climate change and insect pests. CABI International, Wallingford. <https://doi.org/10.1079/9781780643786.0001>
- Beck SD (1983) Insect thermoperiodism. *Annu Rev Entomol* 28:91–108
- Bitsch J, Barbier Y, Gayubo F, Schmidt K, Ohl M (1997) Hyménoptères Sphecidae d'Europe occidentale. Volume 2. Faune de France 82. Federation Francaise des Societes de Sciences Naturelles, Paris
- Blois JL, Zarnetske PL, Fitzpatrick MC, Finnegan S (2013) Climate change and the past, present, and future of biotic interactions. *Science* 341:499–504. <https://doi.org/10.1126/science.1237184>
- Blösch M (2000) Die Grabwespen Deutschlands: Lebensweise, Verhalten, Verbreitung. Die Tierwelt Deutschlands 71, Goecke & Evers, Keltern
- Booth TH (2018) Why understanding the pioneering and continuing contributions of BIOCLIM to species distribution modelling is important. *Austral Ecol* 43:852–860. <https://doi.org/10.1111/aec.12628>
- Booth TH, Nix HA, Busby JR, Hutchinson MF (2014) BIOCLIM: the first species distribution modelling package, its early applications and relevance to most current MaxEnt studies. *Divers Distrib* 20:1–9. <https://doi.org/10.1111/ddi.12144>
- Braestrup FW, Nielsen E (1941) *Philanthus triangulum* F. i Danmark. Vidensk Meddelelser Fra Den Naturhistoriske Foren i Kjöbenhavn 104:353–365
- Brygadyrenko V, Avtaeva T, Matsyura A (2021) Effect of global climate change on the distribution of *Anchomenus dorsalis* (Coleoptera, Carabidae) in Europe. *Acta Biol Sib* 7:237–260. <https://doi.org/10.3897/abs.7.e72409>
- Bueno Marí R, Jiménez-Peydró R (2013) Global change and human vulnerability to vector-borne diseases. *Front Physiol* 4:158. <https://doi.org/10.3389/fphys.2013.00158>
- Burger F (2007) Nachtrag zur Checkliste der Grabwespen (Hymenoptera, “Sphecidae”) Thüringens. Checklisten Thüringer Insekten 15:59–60
- Carrasco L, Papeş M, Lochner EN, Ruiz BC, Williams AG et al (2020) Potential regional declines in species richness of tomato pollinators in North America under climate change. *Ecol Appl* 31:e02259. <https://doi.org/10.1002/eap.2259>
- Chae Y, An YJ (2018) Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. *Environ Pollut* 240:387–395. <https://doi.org/10.1016/j.envpol.2018.05.008>
- Clavero M, García-Berthou E (2005) Invasive species are a leading cause of animal extinction. *Trends Ecol Evol* 20:110. <https://doi.org/10.1016/j.tree.2005.01.003>
- Cornelissen B, Neumann P, Schweiger O (2019) Global warming promotes biological invasion of a honey bee pest. *Glob Chang Biol* 25:3642–3655. <https://doi.org/10.1111/gcb.14791>
- Cresswell JE (2017) A demographic approach to evaluating the impact of stressors on bumble bee colonies. *Ecol Entomol* 42:221–229. <https://doi.org/10.1111/een.12376>
- Cudmore TJ, Björklund N, Carroll AL, Staffan Lindgren B (2010) Climate change and range expansion of an aggressive bark beetle: evidence of higher beetle reproduction in naïve host tree populations. *J Appl Ecol* 47:1036–1043. <https://doi.org/10.1111/J.1365-2664.2010.01848.X>
- Damien M, Tougeron K (2019) Prey–predator phenological mismatch under climate change. *Curr Opin Insect Sci* 35:60–68. <https://doi.org/10.1016/j.cois.2019.07.002>
- Dufresne JL, Foujols M-A, Denvil S, Caubel A, Marti O et al (2013) Climate change projections using the IPSL-CM5 Earth System Model: From CMIP3 to CMIP5. *Clim Dyn* 40:2123–2165. <https://doi.org/10.1007/s00382-012-1636-1>
- Dukas R (2001a) Effects of predation risk on pollinators and plants. In: Chittka L, Thomson J (eds) *Cognitive Ecology of Pollination*. Cambridge University Press, Cambridge, pp 214–236
- Dukas R (2001b) Effects of perceived danger on flower choice by bees. *Ecol Lett* 4:327–333. <https://doi.org/10.1046/j.1461-0248.2001.00228.x>
- Dukas R (2004) Bumblebee predators reduce pollinator density and plant fitness. *UW Natl Park Serv Res Stn Annu Reports* 28:94–97. <https://doi.org/10.13001/uwnpsrc.2004.3583>

- Dukas R, Morse DH (2003) Crab spiders affect flower visitation by bees. *Oikos* 101:157–163. <https://doi.org/10.1034/j.1600-0706.2003.12143.x>
- Dyderski MK, Paź S, Frelich LE, Jagodziński AM (2018) How much does climate change threaten European forest tree species distributions? *Glob Chang Biol* 24:1150–1163. <https://doi.org/10.1111/gcb.13925>
- Eid KSA, Abou-Shaara HF (2021) Predicting with the pest status of two main insects that attacking honey bee colonies in Africa based on the future climatic changes. *J Plant Prot Pathol* 12:535–541. <https://doi.org/10.21608/jppp.2021.198240>
- El-Borollosy FM, Wafa AK, El-Hefney AM (1973) Studies on the biology of *Philanthus triangulum* F. Abdel Kader (Hymenoptera: Sphecidae). *Bull Société Entomol D'egypte* 56:287–295
- Elith J, Phillips SJ, Hastie T, Dudík M, Chee Y-E et al (2011) A statistical explanation of MaxEnt for ecologists. *Divers Distrib* 17:43–57. <https://doi.org/10.1111/j.1472-4642.2010.00725.x>
- Else GR (1995a) *Philanthus triangulum* (F.) (Hym., Sphecidae) in southern England in 1994. *Entomol Mon Mag* 131:205–206
- Else GR (1995) Records of *Philanthus triangulum* (F.) (Hym., Sphecidae) in southern England in 1993. *Entomol Mon Mag* 131:24
- Engl T, Bodenstern B, Strohm E (2016) Mycobiota in the brood cells of the European beewolf, *Philanthus triangulum* (Hymenoptera: Crabronidae). *Eur J Entomol* 113:271–277. <https://doi.org/10.14411/eje.2016.033>
- Erlandsson S (1962) The occurrence of *Philanthus triangulum* F. in the Scandinavian countries. (Hym. Sphecidae). *Entomol Tidskr* 83:208–211
- Fahringer J (1922) Hymenopterologische Ergebnisse einer Wissenschaftlichen Studienreise nach der Türkei und Kleinasien (mit Ausschluß des Amanusgebirges). *Arch Für Naturgeschichte* 9:149–222
- Falk SJ (2010) The bee and wasp assemblages (Hymenoptera: Aculeata) of some key heathland sites in the West Midlands region. *Br J Entomol Nat Hist* 23:77–98
- Fielding AH, Bell JF (1997) Review of methods for the assessment of prediction errors in conservation presence/absence models. *Environ Conserv* 24:38–49
- Giliba RA, Mpinga IH, Ndimuligo SA, Mpanda MM (2020) Changing climate patterns risk the spread of *Varroa destructor* infestation of African honey bees in Tanzania. *Ecol Process* 9:48. <https://doi.org/10.1186/s13717-020-00247-4>
- Giorgetta MA, Jungclauss J, Reick CH, Legutke S, Bader J et al (2013) Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5. *J Adv Model Earth Syst* 5:572–597. <https://doi.org/10.1002/jame.20038>
- Goberville E, Beaugrand G, Hautekèete N-C, Piquot Y, Luczak C (2015) Uncertainties in the projection of species distributions related to general circulation models. *Ecol Evol* 5:1100–1116. <https://doi.org/10.1002/ece3.1411>
- Goulson D, Nicholls E, Botías C, Rotheray EL (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347:6229. <https://doi.org/10.1126/science.1255957>
- Guisan A, Thuiller W (2005) Predicting species distribution: offering more than simple habitat models. *Ecol Lett* 8:993–1009. <https://doi.org/10.1111/j.1461-0248.2005.00792.x>
- Haesler V (1977) Der Bienenwolf *Philanthus triangulum* Fabricius in Nordwestdeutschland (Hym. Sphecidae). 1977:289–292. *Allg Dtsch Imkerztg* 11:289–292
- Halsch CA, Shapiro AM, Fordyce JA, Nice CC, Thorne JH et al (2021) Insects and recent climate change. *Proc Natl Acad Sci* 118:e2002543117. <https://doi.org/10.1073/pnas.2002543117>
- Hamm AH, Richards OW (1930) The biology of the British fossorial wasps of the families Mellinidae, Gorytidae, Philanthidae, Oxybelidae and Trypoxylidae. *Trans Entomol Soc London* 78:95–131
- Hanna CJ, Eason PK (2013) Juvenile crab spiders (*Mecaphesa asperata*) use indirect cues to choose foraging sites. *Ethol Ecol Evol* 25:161–173. <https://doi.org/10.1080/03949370.2012.742464>
- Hansen LO (1997) The bee wolf, *Philanthus triangulum* (Hymenoptera: Sphecidae), in Norway. *Entomol Tidskr* 118:189–191
- Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations – the CRU TS3. 10 Dataset 34:623–642. <https://doi.org/10.1002/joc.3711>
- Hijmans RJ (2020) raster: geographic data analysis and modeling (3.3–13) [Computer software]. <https://CRAN.R-project.org/package=raster>
- Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *Int J Climatol* 25:1965–1978. <https://doi.org/10.1002/joc.1276>
- Hijmans RJ, Phillips S, Leathwick J, Elith J (2020) dismo: species distribution modeling (1.3–3) [Computer software]. <https://CRAN.R-project.org/package=dismo>
- Hill MP, Gallardo B, Terblanche JS (2017) A global assessment of climatic niche shifts and human influence in insect invasions. *Glob Ecol Biogeogr* 26:679–689. <https://doi.org/10.1111/geb.12578>
- Hlásny T, Turčáni M (2009) Insect pests as climate change driven disturbances in forest ecosystems. In: Strelcová K, Mátyás C, Kleidon A et al (eds) *Bioclimatology and natural hazards*. Springer, The Netherlands, pp 165–177. [https://doi.org/10.1007/978-1-4020-8876-6\\_15](https://doi.org/10.1007/978-1-4020-8876-6_15)
- Iannella M, D'Alessandro P, Biondi M (2020) Forecasting the spread associated with climate change in Eastern Europe of the invasive Asiatic flea beetle, *Luperomorpha xanthodera* (Coleoptera: Chrysomelidae). *Eur J Entomol* 117:130–138. <https://doi.org/10.14411/eje.2020.015>
- IPCC (2014) Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C et al (eds) *Climate change 2013 – the physical science basis: working group I contribution to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge, pp 1–30. <https://doi.org/10.1017/CBO9781107415324.004>
- Imbach P, Fung E, Lee H, Navarro-Racines C-E, Roubik DW et al (2017) Coupling of pollination services and coffee suitability under climate change. *Proc Natl Acad Sci* 114:10438–10442. <https://doi.org/10.1073/pnas.1617940114>
- Jones CD, Hughes JK, Bellouin N, Hardiman SC, Jones GS et al (2011) The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geosci Model Dev* 4:689–763. <https://doi.org/10.5194/gmd-4-543-2011>
- Jones EI, Dornhaus A (2011) Predation risk makes bees reject rewarding flowers and reduce foraging activity. *Behav Ecol Sociobiol* 65:1505–1511. <https://doi.org/10.1007/s00265-011-1160-z>
- Jones HP, Hole DG, Nickel B, Zavaleta ES (2012) Harnessing nature to help people adapt to climate change: identifying global high-priority areas for coastal ecosystem-based adaptation. *Nat Clim Chang* 2:504–509. <https://doi.org/10.1038/NCLIMATE1463>
- Kaiser A, Merckx T, Van Dyck H (2016) The urban heat island and its spatial scale dependent impact on survival and development in butterflies of different thermal sensitivity. *Ecol Evol* 6:4129–4140. <https://doi.org/10.1002/ece3.2166>
- Kerr JT, Deguise I (2004) Habitat loss and the limits to endangered species recovery in Canada. *Ecol Lett* 7:1163–1169. <https://doi.org/10.1111/j.1461-0248.2004.00676.x>
- Koster A (1985) De Bijenwolf, *Philanthus triangulum* Fabricius, 1775 algemeen op spoorwegterreinen in Zuid-Nederland, Hymenoptera: Sphecidae. *Entomol Ber* 45:75–77
- Laurance WF, Sayer J, Cassman KG (2013) Agricultural expansion and its impacts on tropical nature. *Trends Ecol Evol* 29:107–116. <https://doi.org/10.1016/j.tree.2013.12.001>

- Laws AN (2017) Climate change effects on predator–prey interactions. *Curr Opin Insect Sci* 23:28–34. <https://doi.org/10.1016/j.cois.2017.06.010>
- Leclercq J (1960) Notes détachées sur les Hyménoptères Aculéates en Belgique (43–49). *Bull Ann Société R D'entomologie Belgique* 96:124–132
- Leclercq J (1973) Statistique et destin des guêpes et des abeille solitaires de l'Entre-Vesdre-et-Meuse (Liège, sa banlieue orientale et le Pays de Liège). *Natuurhistorisch Maandbl* 62:159–168
- Leclercq J (1944) Fluctuations du degré d'abondance récemment observées chez certains Hyménoptères aculeates. *Bull Société R Des Sci Liège* 7:262–267
- Maebé K, Hart AF, Marshall L, Vandamme P, Vereecken NJ et al (2021) Bumblebee resilience to climate change, through plastic and adaptive responses. *Glob Chang Biol* 27:4223–4237. <https://doi.org/10.1111/gcb.15751>
- Martín-Vélez V, Abellán P (2022) Effects of climate change on the distribution of threatened invertebrates in a Mediterranean hotspot. *Insect Conserv Divers* 15:370–379. <https://doi.org/10.1111/icad.12563>
- Martínez López O, Koch JB, Martínez-Morales MA, Navarrete-Gutiérrez D, Enríquez E et al (2021) Reduction in the potential distribution of bumble bees (Apidae: *Bombus*) in Mesoamerica under different climate change scenarios: Conservation implications. *Glob Chang Biol* 27:1772–1787. <https://doi.org/10.1111/gcb.15559>
- McMichael AJ (2013) Globalization, climate change, and human health. *N Engl J Med* 368:1335–1343. <https://doi.org/10.1056/NEJMa1109341>
- Menéndez R (2007) How are insects responding to global warming? *Tijdschr Voor Entomol* 150:355–365
- Miller-Struttman NE, Geib JC, Franklin JD, Kevan PG, Holdo RM et al (2015) Functional mismatch in a bumble bee pollination mutualism under climate change. *Science* 349:6255. <https://doi.org/10.1126/science.aab0868>
- Monceau K, Maher N, Bonnard O, Thiéry D (2013) Predation pressure dynamics study of the recently introduced honeybee killer *Vespa velutina*: learning from the enemy. *Apidologie* 44:209–221. <https://doi.org/10.1007/s13592-012-0172-7>
- Muñoz AA, Arroyo MTK (2004) Negative impacts of a vertebrate predator on insect pollinator visitation and seed output in *Chuquiraga oppositifolia*, a high Andean shrub. *Oecologia* 138:66–73. <https://doi.org/10.1007/s00442-003-1405-2>
- Nakazawa T, Doi H (2012) A perspective on match/mismatch of phenology in community contexts. *Oikos* 121:489–495. <https://doi.org/10.1111/j.1600-0706.2011.20171.x>
- Newell P, Paterson M (2010) *Climate capitalism: global warming and the transformation of the global economy*. Cambridge University Press, Cambridge
- O'Donnell MS, Ignizio DA (2012) Bioclimatic predictors for supporting ecological applications in the conterminous United States. U.S. Geological Survey Data Series 691. 10
- Økland B, Flø D, Schroeder M, Zach P, Cocos D et al (2019) Range expansion of the small spruce bark beetle *Ips amitinus*: a newcomer in northern Europe. *Agric For Entomol* 21:286–298. <https://doi.org/10.1111/afe.12331>
- Paż-Dyderska S, Jagodziński AM, Dyderski MK (2021) Possible changes in spatial distribution of walnut (*Juglans regia* L.) in Europe under warming climate. *Reg Environ Chang* 21:18. <https://doi.org/10.1007/s10113-020-01745-z>
- Pearson RG, Dawson TP (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Glob Ecol Biogeogr* 12:361–371. <https://doi.org/10.1046/j.1466-822X.2003.00042.x>
- Pebesma E (2018) Simple features for R: standardized support for spatial vector data. *R J* 10:439–446. <https://doi.org/10.32614/rj-2018-009>
- Pelini SL, Prior KM, Parker DJ, Dzurisin JDK, Lindroth RL et al (2009) Climate change and temporal and spatial mismatches in insect communities. In: Letcher T (ed) Elsevier, Amsterdam, pp 215–231
- Pereira HM, Leadley PW, Proença V, Alkemade R, Scharlemann JPW et al (2010) Scenarios for global biodiversity in the 21st century. *Science* 330:1496–1501. <https://doi.org/10.1126/science.1196624>
- Petrov P (1996) Pchelnyat valk *Philantus triangulum* F. (Hymenoptera: Sphecidae) - edin malko poznat nepriyatel na medonosnitate pcheli v Bulgaria. *Zhivotnovadni Nauk* 33:62–64
- Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions. *Ecol Modell* 190:231–259. <https://doi.org/10.1016/j.ecolmodel.2005.03.026>
- Polce C, Garratt MP, Termansen M, Ramirez-Villegas J, Challinor AJ et al (2014) Climate-driven spatial mismatches between British orchards and their pollinators: increased risks of pollination deficits. *Glob Chang Biol* 20:2815–2828. <https://doi.org/10.1111/gcb.12577>
- Potts SG, Biesmeijer J, Kremen C, Neumann P, Schweiger O et al (2010) Global pollinator declines: trends, impacts and drivers. *Trends Ecol Evol* 25:345–353. <https://doi.org/10.1016/j.tree.2010.01.007>
- Pound KL, Larson CA, Passy SI (2020) Current distributions and future climate-driven changes in diatoms, insects and fish in U.S. streams. *Glob Ecol Biogeogr* 30:63–78. <https://doi.org/10.1111/gcb.13193>
- Puchalka R, Dyderski MK, Vítková M, Sádlo J, Klisz M et al (2021) Black locust (*Robinia pseudoacacia* L.) range contraction and expansion in Europe under changing climate. *Glob Chang Biol* 27:1587–1600. <https://doi.org/10.1111/gcb.15486>
- Puchalka R, Klisz M, Koniakin S, Czortek P, Dylewski Ł et al (2022) Citizen science helps predictions of climate change impact on flowering phenology: a study on *Anemone nemorosa*. *Agric for Meteorol* 325:109133. <https://doi.org/10.1016/j.agrformet.2022.109133>
- Pulawski W (2021) Catalog of Sphecidae. California Academy of Sciences. <https://www.calacademy.org/scientists/projects/catalog-of-sphecidae>. Accessed 11 Aug 2022
- Qin Y, Wang C, Zhao Z, Pan X, Li Z (2019) Climate change impacts on the global potential geographical distribution of the agricultural invasive pest, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae). *Clim Chang* 155:145–156. <https://doi.org/10.1007/s10584-019-02460-3>
- Ramasamy M, Das B (2004) Ramesh R (2022) Predicting climate change impacts on potential worldwide distribution of fall armyworm based on CMIP6 projections. *J Pest Sci* 95:841–854. <https://doi.org/10.1007/s10340-021-01411-1>
- Rathmayer W (1962) Das Paralysisierungsproblem beim Bienenwolf, *Philanthus triangulum* F. (Hym. Sphec.). *Z Vgl Physiol* 45:413–462
- Raven PH, Wagner DL (2021) Agricultural intensification and climate change are rapidly decreasing insect biodiversity. *Proc Natl Acad Sci* 118:e2002548117. <https://doi.org/10.1073/pnas.2002548117>
- Rocchini D, Garzon-Lopez CX (2017) Cartograms tool to represent spatial uncertainty in species distribution. *Res Ideas Outcomes* 3:e12029. <https://doi.org/10.3897/rio.3.e12029>
- Sala OE, Chapin FS III, Armesto JJ, Berlow E, Bloomfield J et al (2000) Biodiversity - global biodiversity scenarios for the year 2100. *Science* 287:1770–1774. <https://doi.org/10.1126/science.287.5459.1770>
- Sánchez-Guillén RA, Hammers M, Hansson B, van Gossom H, Cordero-Rivera A et al (2013) Ontogenetic shifts in male mating preference and morph-specific polyandry in a female colour polymorphic insect. *BMC Evol Biol* 13:116. <https://doi.org/10.1186/1471-2148-13-116>
- Sann M, Niehuis O, Peters RS, Mayer C, Kozlov A et al (2018) Phylogenomic analysis of Apoidea sheds new light on the sister group of bees. *BMC Evol Biol* 18:1–71. <https://doi.org/10.1186/s12862-018-1155-8>

- Saure C (2020) Die Bienen, Wespen und Schwebfliegen (Hymenoptera part.; Diptera: Syrphidae) von Binnendünen in Sachsen-Anhalt. *Berichte Des Landesamtes für Umweltschutz Sachsen-Anhalt* 2:251–278
- Schmitz OJ, Post E, Burns CE, Johnston KM (2003) Ecosystem responses to global climate change: Moving beyond color mapping. *Bioscience* 53:1199–1205
- Simonthomas RT, Poorter E (1972) Notes on the behaviour of males of *Philanthus triangulum* (F.) (Hymenoptera, Sphecidae). *Tijdschr Voor Entomol* 115:141–151
- Simonthomas RT, Simonthomas AMJ (1980) *Philanthus triangulum* and its recent eruption as a predator of honeybees in an Egyptian oasis. *Bee World* 61:97–107
- Smit J, de Boer R (2008) *Philanthus triangulum* (Hymenoptera; Crabronidae) new for the fauna of the Canary Islands. *Linzer Biol Beiträge* 40:897–900
- Smith F (1858) Catalogue of British fossorial hymenoptera, formicidae and vespidae, in the collection of the British Museum. London
- Strohm E, Linsenmair KE (1997) Low resource availability causes extremely male-biased investment ratios in the European beewolf, *Philanthus triangulum* F. (Hymenoptera, Sphecidae). *Proc R Soc Lond Ser B Biol Sci* 264:423–429. <https://doi.org/10.1098/rspb.1997.0060>
- Sullivan M (2014) Measures of central tendency. In: Sullivan M (ed) *Fundamentals of Statistics. Informed Decisions Using Data*, 4th edn. Pearson, Boston, pp 117–130
- Tam J, Mcdaniels TL (2013) Understanding individual risk perceptions and preferences for climate change adaptations in biological conservation. *Environ Sci Policy* 27:114–123. <https://doi.org/10.1016/j.envsci.2012.12.004>
- Thuiller W, Guéguen M, Renaud J, Karger DN, Zimmermann NE et al (2019) Uncertainty in ensembles of global biodiversity scenarios. *Nat Commun* 10:1446. <https://doi.org/10.1038/s41467-019-09519-w>
- Tinbergen N (1958) *Curious naturalists*. Basic Books, New York
- Travis JMJ, Delgado M, Bocedi G, Baguette M, Bartoń K et al (2013) Dispersal and species' responses to climate change. *Oikos* 122:1532–1540. <https://doi.org/10.1111/j.1600-0706.2013.00399.x>
- Twerd L, Krzyżyński M, Waldon-Rudzionek B, Olszewski P (2017) Can soda ash dumping grounds provide replacement habitats for digger wasps (Hymenoptera, Apoidea, Spheciformes)? *PLoS ONE* 12:e0175664. <https://doi.org/10.1371/journal.pone.0175664>
- van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A et al (2011) The representative concentration pathways: an overview. *Clim Chang* 109:5. <https://doi.org/10.1007/s10584-011-0148-z>
- Vanhanen H, Veteli TO, Päävinen S, Kellomäki S, Niemelä P (2007) Climate change and range shifts in two insect defoliators: gypsy moth and nun moth – a model study. *Silva Fenn* 41:469. <https://doi.org/10.14214/sf.469>
- Vannote RL, Sweeney BW (1980) Geographic analysis of thermal equilibria: a conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. *Am Nat* 115:667–695
- Willets E, Guadagno L, Nyman N (2010) *Addressing climate change - issues and solutions from around the world*. IUNC, Gland, Switzerland

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## Authors and Affiliations

Piotr Olszewski<sup>1</sup>  · Marcin K. Dyderski<sup>2</sup>  · Łukasz Dylewski<sup>3</sup>  · Petr Bogusch<sup>4</sup>  · Christian Schmid-Egger<sup>5</sup> · Toshko Ljubomirov<sup>6</sup>  · Dominique Zimmermann<sup>7</sup>  · Romain Le Divelec<sup>8</sup>  · Bogdan Wiśniowski<sup>9</sup>  · Lucyna Twerd<sup>10</sup>  · Tadeusz Pawlikowski<sup>11</sup> · Maurizio Mei<sup>12</sup> · Alexandra Florina Popa<sup>13,14</sup> · Jakub Szczypek<sup>11</sup> · Tim Sparks<sup>3</sup>  · Radosław Puchałka<sup>11,15</sup> 

<sup>1</sup> Natural History Museum, Faculty of Biology and Environmental Protection, University of Łódź, Kilińskiego 101, 90-011 Łódź, Poland

<sup>2</sup> Institute of Dendrology, Polish Academy of Sciences, Parkowa 5, 62-035 Kórnik, Poland

<sup>3</sup> Department of Zoology, Poznań University of Life Sciences, Wojska Polskiego 71C, 60-625 Poznań, Poland

<sup>4</sup> Department of Biology, University of Hradec Králové, Rokytanského 62, 500 Hradec Králové, Czech Republic

<sup>5</sup> Independent Researcher, Fischerstr.1, 10317 Berlin, Germany

<sup>6</sup> Bulgarian Academy of Sciences, Institute of Biodiversity and Ecosystem Research, Tzar Osvoboditel Boulevard 1, Sofia 1000, Bulgaria

<sup>7</sup> 2nd Zoological Department, Natural History Museum Vienna, Burggring 7, 1010 Vienna, Austria

<sup>8</sup> Observatoire Des Abeilles, 87 rue de Courcelles, 75017 Paris, France

<sup>9</sup> College of Natural Sciences, University of Rzeszów, Ćwiklińskiej 1A, 35-601 Rzeszów, Poland

<sup>10</sup> Department of Environmental Biology, Kazimierz Wielki University, Ossolinskich 12, 85-093 Bydgoszcz, Poland

<sup>11</sup> Department of Ecology and Biogeography, Nicolaus Copernicus University, Lwowska 1, 87-100 Toruń, Poland

<sup>12</sup> Department of Biology and Biotechnology, Sapienza University of Rome, Piazzale A. Moro 5, 00185 Rome, Italy

<sup>13</sup> Grigore Antipa National Museum of Natural History, Kiseleff 1, 011341 Bucharest, Romania

<sup>14</sup> Faculty of Biology, University of Bucharest, Splaiul Independentei 91-95, R-050095 Bucharest, Romania

<sup>15</sup> Centre for the Climate Change Research, Nicolaus Copernicus University, Lwowska 1, 87-100 Toruń, Poland