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Applying geostatistical hotspot analyses to a ‘double-invaded’ plant–pest co-occurrence scenario

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Summary

Invasive alien species represent a multifaceted management problem in terms of threats to biodiversity and ecosystems and their impacts on agriculture and human well-being. *Ambrosia artemisiifolia* is an invasive alien plant in Europe that affects the human population as its already highly allergenic pollen can interact with air pollutants, resulting in detrimental effects on health. In this context, the invasive beetle *Ophraella communa* was proposed as a biocontrol agent of *A. artemisiifolia*, as it feeds on its leaves, leading to a decrease in pollen production. This paper takes advantage of the different co-occurrence classes obtained by the ecological niche models inferred for both of these species based on current and future climatic conditions. We integrate them with spatial data regarding major air pollutants (nitrogen dioxide and fine particulate matter). We couple this information with European human population density data at a narrow territorial scale to infer current and future statistically significant hotspots of health risk. The Netherlands and the UK host the widest hotspots within their national territory for both current (7.09% and 3.54%, respectively) and future (15.04% and 6.70%, respectively) scenarios. Considering the alarming results obtained for some areas, the monitoring and biocontrol of *A. artemisiifolia* should be applied as a European strategy.

Introduction

Invasive alien species (IAS) can impact agricultural and livestock systems (Gil et al. 2017), whole ecosystems (Milanović et al. 2020) and human health (Mazza & Tricarico 2018). All of these issues may be caused by potentially just one IAS becoming established successfully in a specific area; the constraints reported by the biotic–abiotic–movement diagram (Soberon & Peterson 2005) well summarize this complexity. Abiotic factors such as temperature and precipitation heavily influence the distribution of many species (Lewis et al. 2017). The accessibility of areas is an important factor in the colonization of areas by an IAS (Arim et al. 2006); human-mediated transportation plays an essential role in this regard (Ascensão & Capinha 2017). In addition, the co-occurrence of species that may ecologically interact with an IAS becoming established in a certain area is a fundamental point to consider when attempting to manage an invasion (Buttenschøn et al. 2010, Lommen et al. 2017).

The study of plant invasions and their ecological implications has gained significant attention in recent years, as global environmental changes continue to reshape ecosystems worldwide. Plant invasions, which refer to the establishment and rapid spread of non-native plant species in ecosystems, pose a substantial threat to biodiversity, ecosystem functioning and ecosystem services (Pyšek et al. 2010, Vilà et al. 2011). Understanding how environmental changes influence the success and impacts of plant invasions is crucial for developing effective management strategies and mitigating the negative consequences of such invasions. Numerous studies have highlighted the role of environmental changes, including climate change, land-use modifications and alterations in disturbance regimes, as key drivers of plant invasions (Dukes & Mooney 1999, Simberloff et al. 2013, Seebens et al. 2017). These changes can create novel ecological conditions, providing favourable opportunities for non-native plants to establish and outcompete native species. However, the specific mechanisms by which environmental changes influence plant invasions are complex and multifaceted, requiring further investigation.

The establishment of IAS can be explained by the great influence exerted by propagule pressure (i.e., the quantity and frequency of introductions of individuals or reproductive units). Numerous studies have highlighted the crucial role of this phenomenon in determining the invasion success and ecological impacts of IAS (Colautti & MacIsaac 2004, Lockwood et al. 2005, Blackburn et al. 2011). The abundance and frequency of introductions can enhance genetic diversity, facilitate adaptation to new habitats and overcome stochastic events and ecological barriers, ultimately promoting the successful establishment of IAS (Lockwood et al. 2005, Simberloff 2009). Therefore, understanding and managing propagule pressure are vital for effective prevention and control strategies aimed at mitigating the impacts of IAS on ecosystems and biodiversity conservation, especially in the context of other ecological pressures. Indeed, as a cross-cutting phenomenon, climate change affects both abiotic and biotic factors and may favour the establishment of IAS (De Simone et al. 2020, Iannella et al. 2021a). For example, amongst many others, the common ragweed *Ambrosia artemisiifolia* L., an IAS from North America, has been established in Europe since the nineteenth century (Hegi 1918, Chauvel et al. 2006), damaging agriculture (Barnes et al. 2018) and human health (Bonini et al. 2016) with its highly allergenic pollen (Plank et al. 2016, Cardarelli et al. 2018). Moreover, *A. artemisiifolia* is a pioneer plant that emerges from a durable, dense soil seed bank, especially if the ground is disturbed, such as in agricultural contexts (Simard et al. 2020); it is also observed to grow outside agricultural areas, colonizing cities and causing serious human health problems. Numerous studies have drawn attention to the accelerated invasion of this species, its increased pollen production (Ziska & Caulfield 2000, Wayne et al. 2002, Bullock et al. 2012, Chapman et al. 2016), as well as its late pollen production, dependent in turn on the habitats in which it occurs (Fumanal et al. 2007), with related negative effects on human well-being stemming from its earlier and longer pollen seasons (see Beggs & Bambrick 2005). In addition, evidence for the long-distance dispersal of *A. artemisiifolia* pollen suggests its remarkable capability for extensive transportation (and, thus, pollinosis outbreaks) and concurrent great seed dispersal, with subsequent establishment in new areas (Šikoparija et al. 2013, Grewling et al. 2019). Climate change is also worsening this issue (Hamaoui-Laguel et al. 2015).

Many efforts have been made to control (or even eradicate) this species (Vincent et al. 1992, SMARTER Project 2016). Some researchers proposed using the ragweed leaf beetle *Ophraella communa* LeSage (Chrysomelidae, Galerucinae), an IAS itself that feeds on *A. artemisiifolia*, to control the plant (Zhou et al. 2014, Sun et al. 2017). In fact, *O. communa* defoliates and leads to a decrease in common ragweed pollen production, concurrently causing a reduced level of damage to cultivated plants with which *A. artemisiifolia* usually co-occurs (e.g., sunflower crops; Dernovici et al. 2006). This last point has raised the interest of researchers over the past 30 years, especially after *O. communa*'s proposal as a biological control agent for ragweed in Australia was rejected (Palmer & Goeden 1991). Today, its potential use is being re-assessed (Müller-Schärer et al. 2023). Indeed, despite extensive tests having been conducted to ensure the host specificity of *O. communa* in various regions of its secondary range, there are still concerns regarding the actual risk of infestation that could affect sunflowers or other Asteraceae crops (Jin et al. 2023). These concerns also derive from the fact that *O. communa* feeds on other plants, such as cockleburs (e.g., *Xanthium strumarium* L.), giant ragweed (*Ambrosia trifida* L.), the IAS feverfew (*Parthenium hysterophorus* L.) and species of commercial interest, such as the Jerusalem artichoke (*Helianthus tuberosus* L.; Jin et al. 2023).

The ragweed leaf beetle *O. communa*, native to the south-eastern area of North America, was first found in two European countries in 2013 feeding on *A. artemisiifolia*, fortuitously demonstrating its potential for biological control (Müller-Schärer et al. 2014). In fact, this oligophagous species feeds on several Asteraceae, including *A. artemisiifolia*, on which it lays its eggs and its larvae develop. This species is also found in other secondary ranges than Europe, such as some Asian countries (China, South Korea and Japan; Meng & Li 2005, Nishide et al. 2015, Kim 2018).

Europe represents the study area of the present research, where the two target species, *A. artemisiifolia* and *O. communa*, co-occur. Iannella et al. (2019a) investigated the simultaneous invasion dynamics of these two species in Europe. Recognizing the potential of *O. communa* as a biological control agent for the invasive *A. artemisiifolia*, the researchers employed a multifaceted approach, combining ecological niche modelling (ENM), remote sensing and geographic information system (GIS) techniques. The objective was to assess the effectiveness of this biocontrol strategy under three distinct future climatic scenarios. The research not only laid the groundwork for more in-depth studies, but also identified specific European regions where the co-occurrence of these two species would be probable in the future. Such insights are crucial for pinpointing areas where biocontrol interventions could yield the most significant benefits. However, a notable finding from their study was the prediction that, in some European countries, *A. artemisiifolia* is poised for a more extensive expansion than *O. communa* in future scenarios. This suggests potential challenges in solely relying on *O. communa* as an effective biological control agent, emphasizing the need for continuous monitoring and possibly the integration of other control measures. In this research, we go deeper in assessing the impacts of *A. artemisiifolia* allergenicity in both current and future scenarios, using ground and remotely sensed information regarding environmental factors acting as adjuvants of common ragweed's allergenicity. Some air pollutants may interact with airborne pollens, increasing the negative impacts on human health, with nitrogen dioxide (NO_2) and fine particulate matter (PM) recognized to be the main drivers of this (Reinmuth-Selzle et al. 2017, Oduber et al. 2019). NO_2 is a common by-product of combustion derived from human activities (e.g., vehicular traffic, industry and household activities) and increases the allergenicity of *A. artemisiifolia* pollens (Ghiani et al. 2012, Zhao et al. 2016, Reinmuth-Selzle et al. 2017). In addition, its non-homogeneous diffusion and clustering behaviour (Misra et al. 2021) and its influence on *A. artemisiifolia* pollen release per inflorescence (Cheng et al. 2023) make it a detrimental pollutant for human health. Atmospheric PM, made up of primary and secondary particles, is one of the main atmospheric pollutants. Primary PM is generated by road transport, combustion (mainly coal burning) and other industrial processes, while secondary PM is generated through chemical reactions between different primary particulates in the atmosphere. Particulates are classified into different categories based on their aerodynamic diameters. The fine PM ($PM_{2.5}$, particle size 0.1–2.5 μm) considered in this study can penetrate the alveoli and terminal bronchioles. PM exposure has significant effects on people with asthma and allergic rhinitis (Dunlop et al. 2016, Luo et al. 2020, Pawankar et al. 2020), but the mechanism by which PM affects people with these diseases is not fully understood (Wu et al. 2018). Its interaction with *A. artemisiifolia* pollen has also been studied (Gleason et al. 2014, Magyar et al. 2022), indicating higher levels of pollen sensitization when they co-occur.

We first assessed the overlap of NO_2 and $PM_{2.5}$ concentrations in European territory with a co-occurrence of *A. artemisiifolia* and *O. communa* in current and future scenarios, considering both climate change scenarios and variations in pollutant emissions. We chose to use the previous climate change predictions from Iannella et al. (2019a) since they are the results (and can act as a proxy; see Rasmussen et al. 2017) of CO_2 and a warmer climate, variables that have positive relationships with pollen production (Hamaoui-Laguel et al. 2015, El Kelish et al. 2014).

Then, we mapped the areas of significant threat to human health, considering population density and evaluating risk for each European country. Finally, we carried out a hotspot analysis to assess European regions in which a statistically significantly high risk of potential allergenicity of *A. artemisiifolia* could occur.

Methods

Geographical data and spatial analyses

All of the spatial processes are based on the geographical data of Iannella et al. (2019a; available upon request). The vector data deriving from the intersection of the three-class climatic ecological niche models inferred for the two target species were used as a base for the analyses performed in the present research. Specifically, these maps are composed of all of the combinations of three suitability classes (class 1: low suitability; class 2: medium suitability; class 3: high suitability, which represent the 0.33–0.66–0.99 suitability intervals, respectively, as reported in Fig. S1a, together with the target species' occurrences). Consequently, certain combinations (such as *O. communa* scoring the lowest class (1)–*A. artemisiifolia* scoring the highest class (3) or others, such as 1–2 and 2–3, corresponding to the *O. communa*–*A. artemisiifolia* combination) pose the highest risk to human health. This is because *O. communa* may lack the suitable climatic conditions necessary for co-occurrence and, therefore, cannot effectively act as a biological control agent for *A. artemisiifolia*. These spatial data were gathered for the current and the 2050 future climatic scenarios (specifically, Representative Concentration Pathway 8.5, hereafter named RCP8.5).

Spatial data for air pollutants were obtained from the European Environment Agency (EEA) geospatial data catalogue (https://sdi.eea.europa.eu/catalogue/srv/eng/catalog.search#/home). Two of the most dangerous air pollutants for health were chosen for the current scenario (with 2018 being the last year available), namely NO_2 and fine PM ($PM_{2.5}$; Fig. S1b,c). These also represent the only pollutants for which future estimates are available to date based on RCP8.5 (Colette et al. 2013). Thus, an RCP8.5-based future data spatialization was performed, following the indications of Colette et al. (2013), so as to perform spatial analyses based on consistent data (i.e., projections of both climatic suitability-based co-occurrence maps and pollutant distributions).

Demographic data arranged according to the Nomenclature of Territorial Units for Statistics (NUTS3) classification were obtained from the Eurostat web portal (https://appsso.eurostat.ec.europa.eu) for both the current and future years (in our case, 2018 and 2050). NUTS3 represents a hierarchical system of subdivision of the economic territory of the European Union (EU) and the UK for the collection, development and harmonization of European statistics at the regional level. Furthermore, due to the withdrawal of the UK from the EU, data for future demographic projections were obtained from the UK Office for National Statistics (https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/). These data are represented in Fig. S1d.

We processed pollutant data based on the classification of the EEA (Ortiz et al. 2020), which suggests division into six classes of increasing concentration. This permitted us to operate with comparable spatial classes of health risk for both NO_2 and $PM_{2.5}$. In addition, considering that the same number of classes was given from Iannella et al. (2019a) for health risk, an appropriate index was built regarding both the species co-occurrence and the air pollutants. We calculated this as the sum of both pollutants and co-occurrence suitability classes for each feature. Finally, the results obtained were weighted according to the demographic value (i.e., multiplying it by the corresponding human population density value; Fig. 1), thus taking into account the exposure of a high (or low) number of individuals, considering the fact that more human-dense areas bear a higher probability of health issues.

The hotspot analysis was carried out in *ArcGIS Pro 3.0*, which identifies statistically significant hotspots and coldspots using the Getis–Ord Gi* (Ord & Getis 1995, Getis & Ord 2010) statistic. Consideration of the scale of analysis, the distribution of the data, outliers and potential biases is crucial to ensure reliable and meaningful results are obtained when utilizing the Getis–Ord Gi* statistic in spatial analysis (Haining 1993). For instance, this statistic can be influenced by the presence of spatial biases (e.g., unequal population densities or sampling biases), which can introduce artefacts and affect the reliability of hotspot or coldspot detection (Fotheringham & Wong 1991). Thus, we incorporated into the process the false rate detection correction (ESRI Inc. 2022), a procedure to potentially adjust the critical p-value thresholds, accounting for multiple testing and spatial dependency. The incorporation of this supplementary algorithm to assess statistical significance and uncertainty improves the stability and interpretation of the spatial statistics (Anselin 1996). Moreover, given the complete coverage of the spatial data we used in relation to our study area and the nature of the data themselves (continuous rasters), any possible spatial bias is further lowered.

The Getis–Ord Gi* statistic analysis thus results in p-values determining the statistical significance of the hotspot or coldspot and a coupled z-value, referring to the 'strength' of the spatial feature, as in studies of biogeography (Iannella et al. 2019b, 2020), nature conservation (Iannella et al. 2021b), economics (Sánchez-Martín et al. 2019) and human health (De Giglio et al. 2019).

To encompass all of the possible spatial patterns in terms of variability of the target species co-occurrence classes, the chosen atmospheric pollutants (NO_2 and $PM_{2.5}$) and the population density, the species' co-occurrence- and air pollutants-based index, calculated as described above, was used to infer the hotspots. The 'inverse distance' spatial conceptualization sub-algorithm available in the hotspot analysis of *ArcGIS Pro 3.0* was used to down-weigh the influence of features based on distance decay (i.e., all features impact or influence each other, but the farther away a feature is, the smaller the impact it has; this sub-procedure was chosen as it particularly well suited for analysing continuous data; ESRI Developer 2011). In this case, the features considered by the hotspot analysis are the products of the index we built, which is the value reported for all of the territorial units deriving from the NUTS3 database.

Finally, we assessed possible statistically significant differences in the z-values obtained from the hotspot analysis performed for both current and future scenarios for each country considered.

Abbreviations used

To optimize layout, country names reported in the figures are abbreviated as follows: Albania (AL), Austria (AT), Belgium (BE), Bulgaria (BG), Croatia (HR), Czechia (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (EL), Hungary (HU), Iceland (IS), Ireland (IE), Italy (IT), Latvia (LV), Liechtenstein (LI), Lithuania (LT), Luxembourg (LU),

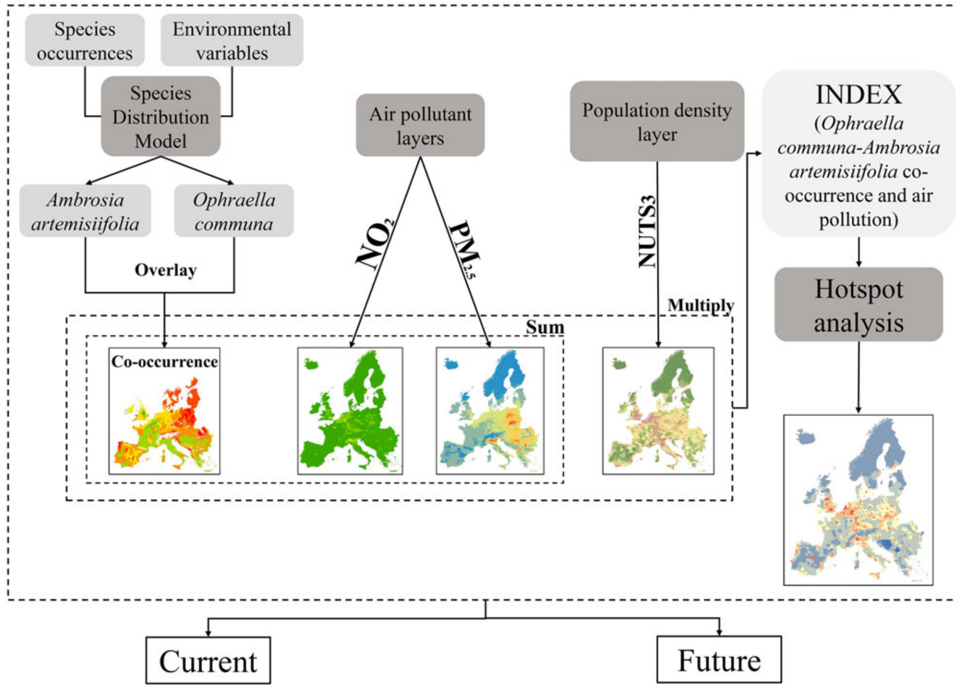

Figure 1. Complete workflow adopted for the analyses. NO_2 = nitrogen dioxide; $PM_{2.5}$ = fine particulate matter (particle size 0.1–2.5 μm).

Montenegro (ME), the Netherlands (NL), North Macedonia (MK), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Serbia (RS), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), Switzerland (CH), Turkey (TR) and the United Kingdom (UK).

Results

The hotspot analysis considering the areas where both the highest z-scores (Fig. 2a) and the three highest confidence intervals ($p = 90\%$, 95% and 99%; Fig. 2b) occur highlighted a current pattern of 212 hotspots of potential allergenicity of *A. artemisiifolia* in Europe (a complete and detailed list of the NUTS3 hotspots is given in Table S1a). The highest percentage of hotspots ranges from the results obtained for the Netherlands (7.09% of the entire national territory) to Norway (0.06%; Fig. 2c).

The hotspot analysis also highlighted 240 hotspots for 2050 (Fig. 3a,b; a complete and detailed list of the NUTS3 hotspots is given in Table S1b), in which the highest values are reported for the Netherlands (15.04%) and the UK (6.70%), while the lowest values are reported for Norway (0.11%) and Romania (0.10%; Fig. 3c).

There were two noticeable coldspots (in terms of low z-score values) in the Balkans in the current scenario and in the future projection. In fact, a p-value between 0.85 and 0.88 was obtained for these areas, which therefore does not exceed the threshold of 0.90 (chosen to identify significant patches).

The change between the current and future scenarios varied amongst the countries (Fig. 4). In general, and for practically all of the countries, a considerable increase in the z-values in each of the hotspots considered (the patches with the highest confidence intervals) is observed, with the northern European countries reporting the highest positive changes in the future (Fig. 4). In addition, when considering percentage change in number of hotspots, the greatest hotspot changes are predicted for the Netherlands (+7.95%), Portugal (+3.66%), Switzerland (+3.47%), the UK (+3.15%), Spain (+1.37%), Ireland (+0.70%) and Croatia (+0.27%; Table S2). Belgium was the only country for which a negative difference was reported, with the number of hotspots within its borders decreasing by 0.58% (Table S2).

When assessing the differences between the z-values obtained for the current and future conditions for the various countries, we found no normal distributions. Therefore, we performed a Kruskal–Wallis test (significance at $p = 0.05$) amongst all of these, obtaining significant differences between each ($\chi^2 = 344\ 319$, $df = 69$, $p = 0$). When comparing each pair for a country (i.e., current–future) using a Mann–Whitney U test (significance at $p = 0.05$), we also obtained statistically significant differences between all pairs for every country; the results for each pair are reported in Table S3.

Discussion

This study incorporates the impacts of climate change on the distribution of *A. artemisiifolia* and one of its antagonists (*O. communa*), relating their predicted co-occurrence to both the air quality and population density and finally assessing overall impacts at a continental scale.

In Iannella et al. (2019a), ecological differences were found between the climatic preferences of the two study species, highlighting the greater adaptability of *A. artemisiifolia* compared to *O. communa*. In fact, many studies (Zhou et al. 2010, Bonini et al. 2016, Iannella et al. 2019a) confirm that *O. communa*, from a bioclimatic point of view, cannot stem the advance of *A. artemisiifolia* alone, as it is more sensitive to adverse climatic conditions than its host plant. Despite this, the biocontrol exerted by this leaf beetle on this invasive plant exists (Bonini et al. 2016) and could be of primary importance due to the harmful effects of *A. artemisiifolia* on the agricultural and health sectors (Schaffner et al. 2020).

The study of Iannella et al. (2019a) focused on climatic and biogeographical aspects only, whereas this study considers the existing co-occurrence between the two target species in parallel with other factors, such as some of the most dangerous air

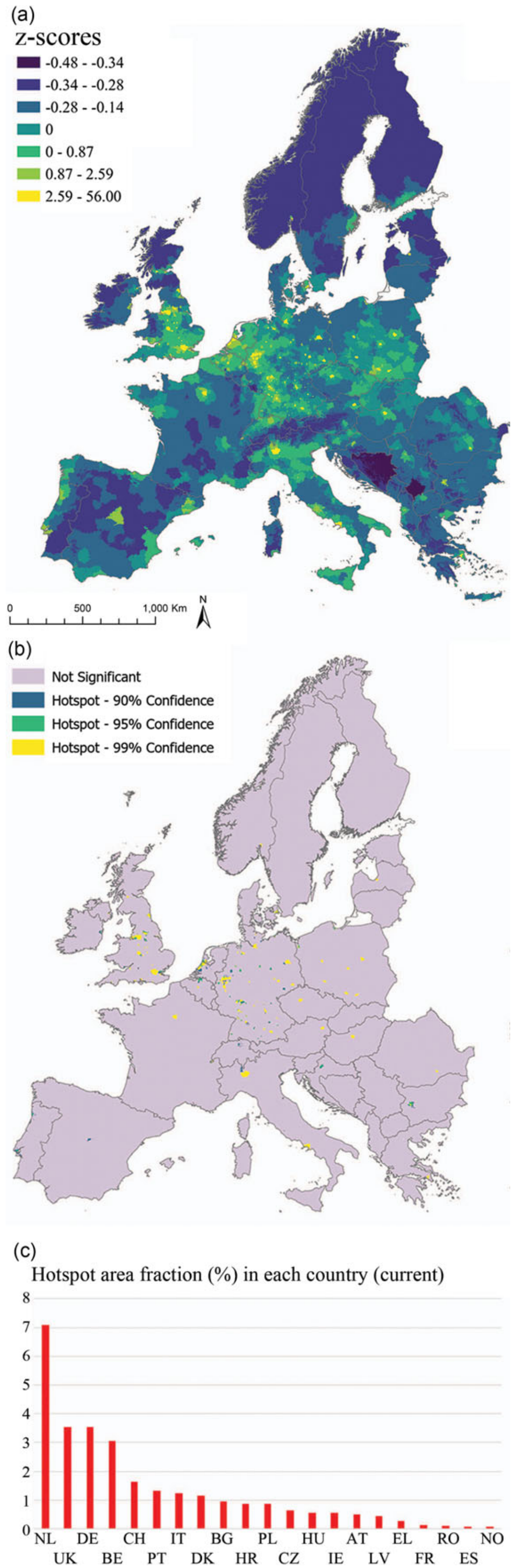

Figure 2. Current hotspots built upon the index based on *Ophraella communa*–*Ambrosia artemisiifolia* co-occurrence and air pollution in terms of the (a) z-scores, (b) p-values and (c) percentage of the total national territory covered by those hotspots (see text for nation abbreviations).

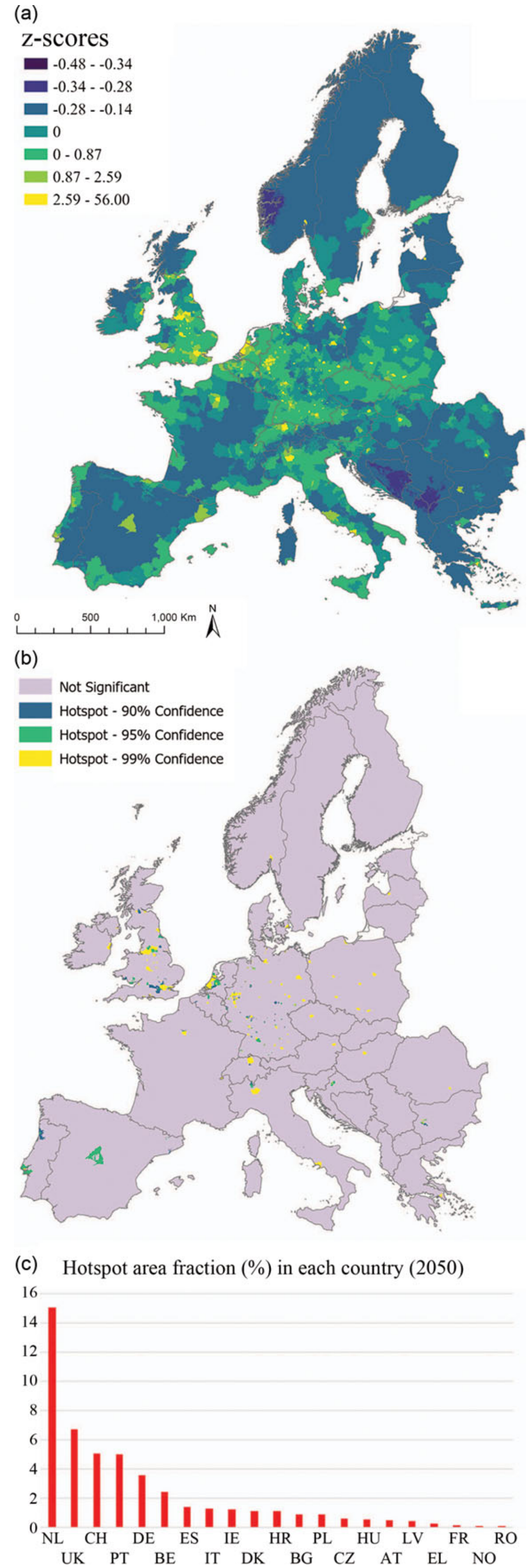

Figure 3. Hotspots in 2050 built upon the index based on *Ophraella communa*–*Ambrosia artemisiifolia* co-occurrence and air pollution in terms of the (a) z-scores, (b) p-values and (c) percentage of the total national territory covered by those hotspots (see text for nation abbreviations).

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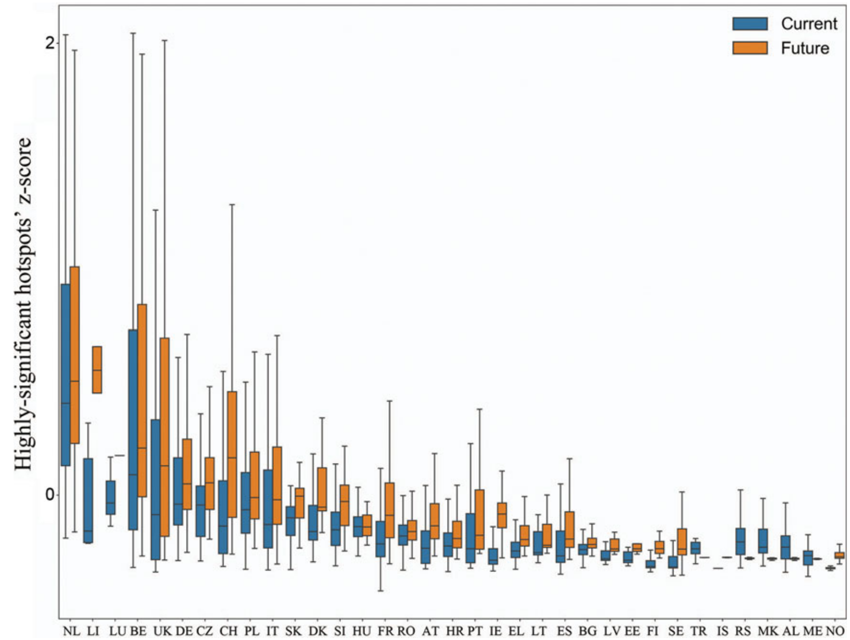

Figure 4. The z-values of the highest confidence interval hotspots for both current and 2050 scenarios for each country (see text for nation abbreviations).

pollutants (NO_2 and $PM_{2.5}$) and human population density. This permits us to statistically summarize and map the connection between a high population density and low air quality (reported to lead to a higher incidence of respiratory diseases) and the pollution-related sensitization towards allergens (Polosa et al. 2002, Diaz-Sanchez et al. 2003, Ledda et al. 2011).

Our hotspot analysis represents a diversified, complex and statistically robust geographical asset that mainly highlights current hotspots in northern European countries (the Netherlands, the UK, Germany and Belgium), where the corresponding hotspot density values (in terms of the hotspot:country area ratio) are higher than 3%. This is consistent with Burbach et al. (2009), who found a rate of more than 80% in terms of pollen sensitization in their population samples for these countries. Regarding the future scenario, in addition to the previously mentioned states, Switzerland and Portugal also show very high hotspot densities (>5%).

Other European countries with known allergy issues caused by *A. artemisiifolia*, such as Italy and Hungary (Bonini et al. 2016, Márk et al. 2016), also resulted in high hotspot densities in the current and future scenarios, although they reported a much lower percentage than the countries with the highest densities in the present study. Indeed, if one observes the spatial model in more detail, a high density of hotspots can be found in a few municipalities (e.g., Milan, Budapest, etc.), which are and will be at high allergy risk. In fact, Bonini et al. (2022) found that the severity of seasonal allergies caused by *A. artemisiifolia* is closely connected to the levels of the plant's pollen present in the atmosphere, with symptom intensity levels associated with specific pollen concentration thresholds. In addition, large municipalities (e.g., Paris, Warsaw, London, Naples, etc.), with strong annual average concentrations of air pollutants and high population densities, are predicted by our analyses to suffer significantly from the presence of *A. artemisiifolia*, particularly in areas where *O. communa*'s ability to act as a biological control agent is not favoured (Iannella et al. 2019a). In addition, the levels at which *O. communa* can control *A. artemisiifolia* are dependent on the seasonality of some climatic factors (Augustinus et al. 2020a) and number of generations (Mouttet et al. 2018), or a combination of the two (Augustinus et al. 2020b), making the framework even more difficult to manage.

Our findings are in line with those of Lake et al. (2017), demonstrating that the sensitization to *A. artemisiifolia* pollen will significantly increase between 2041 and 2060, impacting the European human population. According to the study of Lake et al. (2017), much of the current and future variation is due to the northward expansion of *A. artemisiifolia*, which is consistent with the expansion already observed in the USA (Ziska et al. 2011) and in agreement with our results, showing a shift of the greatest hotspots towards northern Europe. Therefore, if sensitization continues to increase even in areas where *A. artemisiifolia* is relatively rare to date (Lake et al. 2017), some of the countries mentioned above will face severe health and economic risks. Our results corroborate and strengthen the findings of Sun et al. (2017) and Schaffner et al. (2020), who highlighted the often-underestimated effects of *A. artemisiifolia* pollen on human health. In fact, considering that the approach used in Sun et al. (2017) and Schaffner et al. (2020) does not involve human density and other pollutants as we do in our analyses, these results are somewhat alarming. Some areas that are not highlighted by these habitat suitability-based papers for these species represent well-defined (and statistically significant) health risk hotspots, since pollutants and human population density play major roles in this. For instance, this is the case for some of the southern Italy, northern France and central Spain hotspots, where suitability is predicted to be medium (Iannella et al. 2019a) or low (Rasmussen et al. 2017). The multifaceted nature of this management issue can be highlighted using the following example: the major predicted hotspot for southern Italy falls within the district around Naples, in which *A. artemisiifolia*-related pollinosis is not currently recorded. However, the plant was recently found in Latium, a region that borders Campania, the administrative region with Naples as its capital. In the area between these regions are two wide agricultural districts (European Environmental Agency, 2019). Taken together, the vehicular traffic involved in the trade of agricultural goods and the fact that *A. artemisiifolia* spreads through both road dispersal (Lemke et al. 2019) and after soil disturbance (e.g., in agricultural contexts) suggest that colonization will be very likely. As a further issue that could possibly worsen the problem, future climatic projections report that there will be favourable conditions for *A. artemisiifolia* range expansion (Rasmussen et al. 2017, Iannella et al. 2019a).

Control of *A. artemisiifolia* plants is difficult due to their long-lived seeds, resistance to herbicides and ability to regrow after cutting (Brewer & Oliver 2009, Lommen et al. 2018). In addition, recent research has reported the rapid evolution of this plant, resulting in individuals converging towards adaptive traits to a warming climate (Sun et al. 2020). Nevertheless, monitoring the areas subject to the invasion of *A. artemisiifolia* is a crucial element of limiting its spread (Bullock et al. 2012) and of controlling the dispersion of its seeds over long distances, primarily through human activities. Therefore, the strategies suggested for controlling *A. artemisiifolia* are to carefully monitor the distribution of *O. communa* for possible biocontrol applications, bearing in mind that some *O. communa* populations were recently found to rapidly adapt to colder temperatures (Tian et al. 2022) as a result of induced tolerance through trophic transmission (Tian et al. 2023). Thus, as has occurred for other human-mediated translocations aimed at controlling undesired plants, introductions of *O. communa* for biocontrol could also benefit from genetically (Stahlke et al. 2022) and physiologically (Tian et al. 2023) informed studies.

In addition, particular attention should be paid to the improvement of air quality through the concurrent implementation of targeted pollen monitoring strategies. This work could first be implemented in countries that are predicted to suffer more from the future risk increase (i.e., the future appearance or increase of hotspots), although a shared European strategy would be the best approach.

Conclusions

The hotspot analysis indicates that, in Europe, the greatest threat to human health by *A. artemisiifolia* pollen could occur in the north/north-eastern part of the continent, where many countries will become more exposed to such health risks in the future. However, the most significant threats will mostly occur in large cities, where problems due to high population density and air pollutants already exist and where respiratory diseases are and will remain persistent.

Given the rapid spread of *A. artemisiifolia*, monitoring and control measures (using *O. communa*) are essential to stem the advance of this invasive plant. Furthermore, implementing effective strategies to reduce air pollutants could provide significant savings in economic terms and of human lives (Mouttet et al. 2018, Schaffner et al. 2020).

To our knowledge, this study is the first to relate the co-occurrence amongst these target species, air pollutants and population density using advanced geostatistical methods. In light of the broad applicability of this framework, our approach can be applied to any type of invasive plant species and corresponding pests, being applicable to health, agricultural to nature conservation sectors and supporting local policymakers in smart planning processes at all spatial scales. In addition, we provide a starting point for other studies focusing on the relationships between invasive species, human-induced pollution and climate change. Our research sheds light on the multifaceted problems caused by invasive species, emphasizing the threats that they pose to human well-being. By highlighting the negative effects of *A. artemisiifolia* and the interaction of its pollen with air pollutants, this study raises awareness of the importance of managing invasive species to protect native ecosystems and maintain ecological balance. In addition, it helps with the prioritization of monitoring and management efforts. This information can be utilized to implement targeted conservation measures and allocate resources effectively to mitigate the health impacts caused by invasive plants and air pollutants. This paper further advocates for the development of a European strategy to monitor and control *A. artemisiifolia*. By emphasizing the large hotspots of health risk within some national territories, this study highlights the need for collaborative and coordinated efforts to control *A. artemisiifolia* at the European level. This approach promotes the exchange of knowledge and the development of policy frameworks, fostering a unified approach to invasive species management and environmental conservation.

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