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Title: Policies slow biological invasions in Europe, but legacies still matter

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Abstract

Biological invasions are a main cause of biodiversity loss, prompting international agreements and national policies aimed at preventing and managing the introduction, establishment, spread, and impacts of alien species. However, whether these measures have effectively reduced invasions remains uncertain. In this study, we compared the absolute number of established alien species and changes in invasion rates—accounting for invasion timing—across EU countries and the UK with the number and types of policies implemented. Policy effects were analyzed alongside other invasion drivers, such as trade intensity, climate, and geography. We demonstrate for the first time that invasive species policies within the EU and the UK had significant protective effects. Notably, these effects were only evident when examining changes in invasion rates, emphasizing the need to consider invasion dynamics and policy timing. These results should encourage countries to continue managing invasions and contribute to refining strategies for managing alien species.

Keywords: Invasive alien species, Non-native species, Pairwise analysis, Policies, Prevention, Sequential analysis, Spread models

Introduction

Biological invasions are a main driver of biodiversity loss and environmental change, also significantly impacting human well-being and economic activities [1–3]. The number of both established alien species (EAS hereafter) and invasive alien species (the subset of EAS with negative ecological or socio-economic impacts; IAS hereafter) has increased rapidly worldwide over the last decades[4]. Also their numbers and impact are expected to keep increasing due to ongoing international trade, land degradation and climate change[5,6]. Consequently, the management of biological invasions is among the top priorities of many governments, non-governmental organizations, and agencies worldwide[7-9]. Several international agreements and policies have been developed for the prevention and control of biological invasions[2,7]. At European scale, for example, Regulation (EU) 1143/2014 includes a set of policies related to prevention, mitigation, and eradication of IAS. However, management policies may not all be equally protective, and their capacity to prevent invasions may depend on the environmental context and legal or socio-ecological characteristics of the countries or regions considered[10,11].

Prior research has shown that the capacities of countries for managing biological invasions (i.e., their biosecurity regimes or the implementation of national or international agreements) might be associated with different levels of biological invasions[9]. For instance, the development of legislation and regulations, which could be useful to prevent the introduction or establishment of alien species, was more advanced in high-income than low-income countries[10]. At the same time, currently 83% of countries worldwide do not have any national legislation or regulation in place that directly addresses IAS[4]. Additionally, past governance at the country level, which is related to countries' capacity to design and implement policies to manage IAS, is an important driver of the current number of EAS per country[11]. These findings suggest that current EAS numbers not only depend on current policies, but also on legacies of historical socio-economic activities[12,13].

The effectiveness of alien species management policies is influenced by environmental, social, and economic factors, which may cause variations in management policy performances[14-16]. Indeed, trade and environmental similarity have been considered among the most important drivers of biological invasions[17,18]. Trade is associated with both propagule pressure (i.e., the number of introduced individuals per introduction event) and colonization pressure (i.e., the number of species per introduction event). Thus, more trade implies more introduced species and individuals, raising the likelihood that at least one will establish a new population[19-22]. Similarly, geographic variables, such as distance between countries, inland distance from coastlines, population density, size of protected areas, or length of land borders have also been associated with colonization pressure[17,19,23-26]. Climate matching between the native and alien ranges is also known to affect the establishment of introduced species[27-29]. However, the role of regulations and international agreements on the level of biological invasions has hardly been analyzed[30] although this information is needed to assess the effectiveness of current policies.

This study investigates the role of management policies on invasion trends across European Union (EU) countries and the United Kingdom, while also considering other putative drivers, including geographical factors, trade activity, and climate matching. We expect that the number of EAS in a country will be influenced by the number of policies implemented. However, the relationship could be direct, reflecting a high number of policies implemented as a response of countries to historical invasions, or inversely related, reflecting a low number of invasions as a consequence of protective policies. Accordingly, we hypothesize that the direction of the relationship will depend on whether we consider recent or historical invasions. Moreover, many factors influence the number of invasions in a country, and protective policies may reduce invasion rates without completely counteracting all historical or context-specific factors. Therefore, we expect that changes in invasion rates compared to historical levels are likely a more accurate indicator of policy effectiveness than the absolute number of EAS. In our analyses, we examine the total number of EAS, historical and recent invasions (those aligned with the policy implementation period), and changes in invasion rates following policy implementation. Since different types of management policies (e.g., control vs prevention) can vary in their effectiveness[31,32], we differentiate among these types and explore which strategies, if any, are most strongly associated with changes in EAS over time.

Results

Relationships between EAS and Total management

The variable Total management did not exhibit a significant association with absolute numbers of directional EAS (i.e., the Total and Recent Invasions models, Table 1). However, we found a significant inverse relationship between Total management and directional EAS count in the Rate-Change model, suggesting that higher levels of management policies efforts were associated with a reduced number of new EAS, after accounting for background rates of invasion prior to 1995 (Table 1). This pattern remained significant across a range of cut-off years, from 1995 to 2000 (Figure 1).

Regarding the other predictors, in the Total Invasions model, trade between countries was significant and positively associated with directional EAS, indicating that higher levels of trade between countries corresponded to an increased number of established species (Table 1). Country size and climatic distance displayed an inverse relationship with the directional EAS, indicating that smaller countries and those with more similar climates to others had a higher directional EAS shared with other countries.

In the Recent Invasion model, trade and country size appeared as the only significant variables (Table 1). Trade maintained its significance, exerting a direct effect on directional EAS, whereas country size demonstrated a significant inverse effect, meaning smaller countries tended to experience more directional EAS. In the annual variation analysis, trade remained a significant predictor across most cutoff years, while country size was significant only for years 1995–1997 (Figure 1). Sampling effort also presented some significance to directional EAS for a reduced cutoff years, indicating that larger sampling efforts resulted in increased detection of EAS.

In the Rate-Change model, alongside the inverse effect of Total management mentioned earlier, we detected that EAS prior to 1995 was consistently the strongest predictor, showing a robust positive relationship with the number of new invasions (Table 1). Trade was also significantly and directly positively related with the directional EAS count (Table 1) and occurred for most cutoff years (Figure 1). Finally, in the annual variation analysis, sampling effort and population density showed a direct relation with directional EAS number but only for some of the cutoff years.

Relationship between EAS and cluster management

The clustering applied to the three predominant types of management policies (Prevention, Early warning, Control and restoration) resulted in a distinct separation of countries into two groups for each type (Figure 2). Across all three types, countries in Group I demonstrated lower scores of the applied management policies compared to countries in Group II (see Figure 2.b).

When examining the effect of management policy types, we observed a significant and direct effect of Prevention clustered policies with the directional EAS count for the Total Invasions model, indicating that countries in Group II (with more policies on prevention) tend to show higher count of directional EAS (Table 2, Figure 1). However, the effect of individual policy clusters was not detectable for the Recent and Rate-Change models (Table 2, Figure 1).

Regarding the rest of the predictors, we did not observe major changes compared to previous models incorporating the variable Total management (Table 2, Figure 1).

Discussion

The importance of IAS management policies on EAS

Our analysis examined the effect of IAS management policies on the directional EAS count between pairs of countries in the EU and the UK. The results show that Total management (indicating the total number of actions taken by countries' policies regarding the management of biological invasions) was effective in reducing the rate of new invasions experienced by each country. However, the lack of significance in the Recent Invasions model (that uses absolute number of invasions rather than the rate-change values as response variable), suggests that many other factors are at play causing high variation in invasions between countries.

These differences in results could reflect a Simpson's paradox effect[33] where underlying drivers mask protective policy effects, making historical context essential to interpreting recent trends. The directional EAS count did not show a clear relationship with management efforts, likely for two main reasons. First, historically invaded countries tend to implement more prevention policies, which could obscure any protective effects within the model. Second, even though management policies may reduce invasion rates, other persistent drivers such as trade intensity and environmental suitability, continue to contribute to new invasions, sustaining variability. For instance, if trade volume increases—creating opportunities for further invasions—management policies may only partially counterbalance these added risks. Consequently, the Rate-Change model, which accounts for historical trends between countries, proved most sensitive in detecting the impact of management efforts on invasions.

Furthermore, our analysis indicates that invasion history remained the best predictor of future invasions; countries with a higher number of EAS prior to a determined cutoff year (i.e., 1995) also had a greater number of recently recorded EAS. Thus, countries that were more susceptible to invasions in the past continue to be vulnerable, reinforcing the notion that the same factors that drove high introduction rates in the past still influence the current level of invasions[9-12]. This aligns with the concept proposed by Redding et al.[34] of a self-reinforcing process, where established alien species may facilitate the success of new invaders. These findings underscore that altering invasion trajectories remains a challenge, despite the implementation of new regulations and management efforts.

Our analyses show that the ability to detect the influence of management policies diminishes after 2000. This may be due to the smaller window of time considered for recent invasions, which reduces the power to detect significant relationships. This effect may be further exacerbated by reporting lags, defined as the time needed to record a newly established alien species in a country and integrate such data into our database[35]. Consequently, drawing conclusions about recent patterns remains challenging.

Finally, cluster analyses categorized countries based on various types of alien species management policies, revealing distinct levels of management effort among them. While certain strategies—such as prevention, prioritization, and early warning—have proven effective in controlling EAS in specific regions[36,37], their integration into a European-level analysis did not yield significant results in the Rate-Change model. Instead countries with a higher number of prevention policies tended to report a higher absolute number of EAS, based on results from the Total Invasions model. Given that most historical invasions occurred prior to policy implementation, it is likely that this represents a reactive relationship; countries that recognized a greater urgency regarding EAS presence were more inclined to adopt preventative management policies.

The importance of other covariables

Across all models, trade activity among pairs of countries (i.e. import values) was directly associated with the number of directional EAS. This finding aligns with previous studies demonstrating international trade increases the likelihood of introducing alien species as stowaways or traded organisms [11,12,38]. By examining trade dynamics between pairs of countries rather than merely considering total import volumes, we can analyze specific routes for invasive species. Importantly, trade remained important and positive in the Rate-Change model, indicating that higher trade resulted in an acceleration in accumulation of invasions, compared to historical rates in a given country.

Several other variables exhibited relationships with the level of invasion, albeit with varying significance across the different models and years tested. For instance, climatic distance demonstrated an inverse relationship with the directional EAS count in Total Invasions models. In other words, regions that are more ecologically similar tend to share more EAS. This confirms the relevance of species' ecological requirements for establishment[29]. However, this relationship was not observed in the Recent Invasions or Rate-Change models, possibly because of fewer invasions and lower power (for the Recent Invasion model) and a consistent effect (no change in rate in the Rate-Change model). In contrast, an inverse relationship between country size and the number of detected directional EAS was detected across both the Total and Recent models, suggesting that smaller countries often have more directional EAS. This apparently counterintuitive finding might occur if EAS numbers were influenced by a country's relative position to other countries. For instance, countries like Belgium, the Netherlands, Czechia, and Austria, despite their relatively compact size, may have exhibited a high number of EAS arrivals from other countries due to their central location in Europe. The current models does not account for cumulative propagule pressure, which would require a more mechanistic approach[39]. Sampling effort was directly related to the directional EAS number detected, as previously described[40]. However, such effects were only significant in Recent Invasions and Rate-Change models and inconsistently across the cutoff years. Finally, while the effect of population density on absolute directional EAS number was not generally detectable, there was some evidence of effect in the Rate-Change model across a number of cutoff years. This indicates that countries with higher population density had a greater number of new invasions than expected based on historical rates[41].

Understanding biological invasions in Europe

Trade has emerged as the primary driver of alien species movements across European countries[17,21]. Projections suggest that international trade, sustained by expanding infrastructure and increasingly global consumption patterns, will continue to grow in the coming decades[42,43] resulting in a global increase in alien species richness[6]. Our analysis also confirmed that climatic distance has a significant effect on dispersal patterns between countries. Notably, the impacts of climate change vary across geographic regions and taxonomic groups, further shaping these movements. In a context of accelerating climate change, these trends will undoubtedly exacerbate the impacts of biological invasions on biodiversity. Several modelling studies projected an expansion of climatic suitability for alien species in Europe under climate change[44-46], and rising establishment rates have been directly linked to climate change, even when controlling for propagule pressure[47].

The relationship between invasive species numbers and country-specific factors, such as trade volume and GDP, is well-documented[9,21,48]. However, invasions are dynamic processes shaped by specific historic and socio-economic relationships between countries. Understanding EAS flows requires an analysis that goes beyond individual country traits to examine species spread from one country to another[17,38]. A more mechanistic approach, explicitly modelling propagule pressure over time and other invasion history factors, could be an avenue for future EAS research and management. Additionally, a key limitation in current models is the availability of sampling effort data, which remains fragmentary in many regions and taxa. This gap can restrict the robustness of any future models or management policies based on such data. Therefore, addressing these data gaps should be a priority in future research efforts, as it will enhance the reliability of analyses and inform more effective management strategies.

While previous studies have evaluated management strategies regionally[49] or through stakeholder perceptions[50,51], this work represents the first direct assessment of the impact of IAS management policies at a country scale in Europe. Our findings confirm that EU management policies can indeed slow down the rate of biological invasions. This finding highlights the importance of sustained efforts to manage invasive species and offers insights into how policies and their evaluation could be further refined. However, many challenges remain. Many policies remain reactive or fail to progress as quickly as other key drivers of invasion, such as economic growth and trade[10]. Additionally, there is frequently a gap between the policies development and their enforcement in practice. One limitation of our study is the absence of detailed temporal data on policy implementation and its immediate impact, introducing some uncertainty. Furthermore, since management actions often operate at varying scales—regional, local, and species-specific—a multi-scale approach would further enrich the assessment of policy effectiveness. A comprehensive framework that combines enforcement with real-time responsiveness and flexibility in policy adaptation is vital to address the evolving threat of biological invasions. The EU IAS Regulation 1143/2014 marks a crucial step in this direction, offering a unified approach to managing alien species, not only addressing current threats but also preparing for future challenges. Looking forward, policy evaluations should focus on linking actions with long-term outcomes, exploring potential lag phases between implementation and impact, and incorporating a multi-scale perspective.

Conclusions

This study is the first to demonstrate that alien species management policies at a national scale across the EU countries and the UK and multiple taxonomic groups have had a measurable impact in reducing invasion rates, offering a robust and nuanced approach to understanding the effectiveness of such policies. Based on our findings, current policies may help to achieve the Kunming-Montreal Global Biodiversity Framework[7]. The fifth target of this framework aims to eliminate, minimize, or mitigate the impacts of alien species on biodiversity and ecosystem services, and reduce the rates of introduction and establishment of alien species by at least 50 per cent by 2030[7]. However, given that the number of historical invasions remained the strongest predictor of new invasions, additional policies may need to "bend the curve" more, to achieve the desired targets (see Roura-Pascual et al.[16] for a European Management strategy). This highlights the necessity for strengthening and adapting management measures to account for the persistent legacy of past invasions, fostering a more proactive approach to mitigate future risks.

Material and methods

Data on established alien species

We obtained EAS richness (Figure 3) for 28 European countries - i.e. the EU Member States and the UK - for seven taxonomic groups for which country-level data was available: vascular plants[52], ants[53], birds[54], mammal[55], spiders (Nentwig, unpublished data), and amphibians and reptiles[56]. We obtained additional data for all groups from the First Record Database, version 3.1.[57]. Many of these different sources report both established and casual alien species, and we only considered the established ones for analyses. We harmonized data from these different sources and resolved taxonomic discrepancies, by cross-referencing species names to ensure consistency across datasets and removing any redundant entries resulting from taxonomic synonyms. The final dataset included 6667 species (6271 vascular plants; 134 ants; 103 birds; 48 mammals; 50 spiders; and 49 amphibians and reptiles). Details about data treatment are provided in Supplement 1.

Management variables

We obtained information on countries' management policies from Sonigo et al.[58], who examined IAS policies in 28 European countries prior to the establishment of the EU IAS Regulation 1143/2014, most of them dating back to the 1990s and 2000s (Supplement 2 and 3). The report includes 58 country-level criteria related to IAS policies, such as prevention, early warning, control and restoration, financing instruments, strategy development, capacity building, awareness raising, and international cooperation (see detailed list of criteria in Supplement 2). Each criterion was classified by Sonigo et al.[58] as: full coverage (when the country meets the criterion in all relevant aspects), partial coverage (the criterion is addressed only for some taxa or aspects), similarly covered (a country considers some provisions that overlap or may be interpreted as covering the criterion), or not fulfilled (no text or initiative was related to the criterion). We ranked these categories as follows: full coverage = 3, partial coverage = 2, similar covered = 1, and not fulfilled = 0. We then summed the scores across the different policies in each country to create a combined indicator of policy implementation, referred to as 'Total management'.

Additionally, to identify patterns in management policies across countries, we performed a cluster analysis with the 58 country-level criteria related to alien species management policies. This analysis allowed us to group countries into two distinct categories based on similarities on their scores of the applied management policies, reflecting how often those measures co-occur within given countries. We conducted three sets of cluster analyses separately for each of the following types of management measures: (i) prevention, (ii) early warning, and (iii) control and restoration. Specifically, we calculated an Euclidean distance matrix for each type, ensuring there were no correlations above 0.6 and that all Variance Inflation Factor (VIF) scores were below 5 among the policies included in each type. The optimal number of clusters was determined using the silhouette coefficient, which consistently indicated two clusters for each type of management measure. We used the partitioning-around-medoids clustering method that enabled us to categorize countries meaningfully based on their approach to each type of management policy. This method provided a nuanced understanding of how different countries prioritize alien species management strategies, forming distinct groups based on policy emphasis. Unlike techniques such as Principal Component Analysis (PCA), which focuses on data dimensionality reduction, our approach offers a detailed interpretation of the most prevalent strategies within each group of countries. We used the *cluster* package in R 4.1.0[59] for the cluster analysis[60].

Predictor variables

In addition to the quantification of policies across countries, we included other covariables related to geographic, economic, and climatic factors that are known to influence invasion patterns. We also accounted for the potential effect of sampling efforts.

- Geographical data: For each country, we extracted country size (km^2), and the percentage of terrestrial protected area for the year 2020 from the World Bank Data[61], and from the World Data on Protected Areas[62]. Finally, the spatial distance between countries was calculated as the minimum great-circle distance in radians between the borders of two countries.
- Socio-economic data: For each country, we extracted human population density (inhabitants/km^2) and the average import values for each country from 1995 to 2018 using the Open Trade Statistics[63].
- Climatic data: We calculated climatic distance between countries, which quantifies the dissimilarity in climatic characteristics between each pair of countries. We used eight bioclimatic variables obtained from WorldClim[64] at a 10-minute resolution including annual mean temperature, temperature seasonality, mean temperature of the warmest and coldest quarters, annual precipitation, precipitation seasonality, and precipitation of the warmest and coldest quarters. To reduce multicollinearity, we first applied a PCA on the climatic variables. We then calculated the Euclidean distance between country pairs using the mean scores of the first two principal components, which represent over 75% of the total variance.
- Sampling effort. This index, extracted from Dawson et al.[40] and based on Meyer et al.[65,66], represents the mean percentage of completeness of native species inventories for different taxa calculated at a 110x110 km resolution for each country. It was calculated based on the number of GBIF[66] records per unit area accounting for native species number. Similarly to Latombe et al. [11], we used this index to control for differences in data quality between countries in all models.

Statistical analyses

To analyze the level of invasions, we recorded the overlap in EAS composition between each pair of the 28 European countries (i.e., the number of shared species between pairs). We considered the directionality of invasions, hereafter referred to as "directional EAS". Doing so enabled us to describe the invasion patterns within the EU and the UK, where EAS spread from invaded (i) to uninvaded countries (j)[68]. The first occurrence of a species in the EU and the UK was excluded from these analyses, as it does not represent secondary spread. Since we could not know the true source of an invasion when there were multiple potential sources, we considered the temporal order of events. For instance, if species x invaded countries i and j in 1980 and 1982, respectively, country i could be the source for country j but not vice versa. Thus, for country pair source i recipient j, the invasion by species x would be assigned to j, and not i. This was repeated for each species, to obtain the number of species potentially invading recipient j from source i. To do so, we considered the year in which each EAS was first detected in each country from the First Record Database[57]. In cases where the introduction date was unknown, we treated those countries as sources, given that introductions that happened following the application of systematic EU policies are more likely to have been recorded. Because each source and recipient countries appeared multiple times in the analysis, we controlled for pseudo-replication by including both sources and recipient countries as random effects in the model (Eq.1).

We used three models with different metrics of invasion as a response variable and covariables (Figure 4):

- Total Invasions: This model considers the invasion metric that includes all potential invasions from country (i) to country (j) across the entire data range (from 5000 b.c.e. to 2020). We modeled the relationship between the response variable directional EAS and the explanatory variable Total management of the recipient country (j) (Eq.1). In addition, we included the following pair-specific covariables: trade between countries, physical distance between countries, climatic distance index, and the accumulated sampling effort between the two countries as these factors could influence invasions and its detectability from country i to country j. Furthermore, potential covariables like country size, population density, and protected area of the invaded country (j) were also considered.
- Recent Invasions: This model considers as response variable only the directional EAS newly recorded (after 1995) in the recipient country (j). We selected 1995 as the cutoff year since most of the management policies considered, as highlighted by Sonigo et al.[58], were implemented since the mid-1990s. Additionally, this period aligns with the establishment of key international biodiversity agreements, such as those reported by the European Environment Agency[69]. We identified the year of first detection of alien species in each country using the First Records database of Seebens et al.[57]. For species with missing first-detection data, we assumed an introduction date earlier than 1995. The same pair-specific and potential covariables as in the previous model were also considered.
- Rate-Change: In this model, we used the same variables and invasion metric as in the Recent Invasions analysis, focusing on EAS detected after 1995. However, we also included the number of directional EAS recorded prior to 1995 as an additional covariate. We hypothesized such covariate would be correlated with both the number of policies (highly invaded countries in the past may have implemented more policies) and recent invasions (reflecting underlying drivers unaccounted for). This covariate also allowed us to assess the proportional change in newly recorded EAS while accounting for historical effects (i.e., providing the rate-change from past EAS). Although we initially considered using ratios (e.g., newly recorded EAS/past EAS) as the response variable, this approach was discarded due to inflated Type I error rates, as shown in theoretical analyses. Thus, incorporating EAS before 1995 as a covariate enabled us to assess the change in invasion rate more robustly.

An additional fourth model, referred to as the Historic Invasion model, was considered, using only EAS detected prior to 1995 as the invasion metric and is detailed in Supplement 4.

The notation of the models is as follows:

$$(Eq.\,1)\ Y_{i,j} \sim M_j + T_{i,j} + D_{i,j} + C_{i,j} + S_{i,j} + P_j + PA_j + SA_j + (1|i) + (1|j)$$

where subscripts *i* and *j* denote the source and recipient country, respectively; Y was one of two invasion metrics (either total invasions or after different cutoff years; see above); M was a metric of management policies (either total, or clustered, see below); T was trade from *i* to *j*; D was distance between *i* and *j*; C was climatic distance between *i* and *j*; S was the sum of sampling effort in *i* and *j*; P was population size in *j*, PA was protected area in *j*, SA was country size of *j*, and (1|*i*) and (1|*j*) denote the inclusion of random effects terms for both the source and recipient countries. Finally, only when modelling Rate-Change we incorporated Yb1995 that was the directional EAS recorded before 1995 in *j*.

Each response variable as well as all continuous predictor variables were log(X+1) transformed, and then normalized around zero to standardize variables. To avoid multicollinearity, we conducted correlation analyses between predictor variables, ensuring that none had a correlation coefficient higher than 0.6. Additionally, we calculated the VIF and excluded variables with a VIF score over 5. We checked for outliers in our data and ultimately excluded Luxembourg, Malta, and Cyprus due to their outlier status because of their country sizes. Each model was run twice: first, using the predictor variable Total management representing the overall level of management policies; and second, using the cluster-based policy groups for each policy type of the recipient country, which reflect the country's focus on specific types of management policies (i.e., prevention, early warning, and control and restoration). This allowed us to explore which types of management policies (if any) relate most strongly to the directional EAS. We conducted our analysis using linear mixed models with a Gaussian error distribution, employing the *stats* package and *lmerTest*[70] in R 4.1.0[59], and we set the significance level at $\alpha = 0.05$.

Finally, to evaluate how the cutoff years might influence the models Recent Invasions and Rate-Change, we conducted an annual variation analysis, reapplying the models with progressively later cutoff years. This allowed us to observe the evolving role of management over time and assess any temporal shifts in management effectiveness. Our analysis covered the years 1995 to 2008, as more recent EAS data may be incomplete due to time lags between species establishment and detection[35].

Resource availability

The R code and dataset used in this manuscript is available at Zenodo (10.5281/zenodo.14222248). Further information and requests for resources should be directed to the lead contact, Dr. Q. Canelles (quimcanellestrabal@gmail.com).

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Author contribution

Q. Canelles, C. Pérez-Granados, N. Roura-Pascual, and B. Leung contributed to the conception, design, data collection, analysis, and drafting of the manuscript. The remaining authors contributed to data acquisition, interpretation of results, and critical revision of the manuscript.

Conflict of interest

The authors have no conflict of interest to declare.

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Tables and figures

Table 1. Model results: Results of the Total Invasions, Recent Invasions and Rate-Change models for explaining recorded numbers of established alien species (EAS) in the European Union countries and the United Kingdom. Significant variable scores are in bold.

Table 2. Model results with policy clustering. Results of models using clustering for management to explain the number of recorded established alien species (EAS) after 1995 in the European Union countries and the United Kingdom. Significant variable scores are in bold.

Figure 1. **Annual variations analysis.** Annual variation analysis between the years 1995 and 2008 for the Recent Invasions and Rate Change models. Upper panels show the relationships for the models using Total management, while lower panels show the relationships for models using management policies types within the clusters. Red indicates direct relationships between the number of EAS and the predictor variables, while green indicates inverse relationships. Significant relationships ($p < 0.05$) are indicated in dark colors and non-significant ones are in light colors.

Figure 2. Clustering of IAS management policies. Cluster results of the European Union countries and the United Kingdom based on their implementation of three types of invasive alien species policies. The upper panel categorizes countries into two distinct groups, derived from their management policy scores and using partitioning around medoids clustering. This classification is visualized through a multidimensional scaling (MDS) approach, with MDS1 and MDS2 representing the first two dimensions obtained from a Euclidean distance matrix. The lower panel displays the average normalized scores for each policy type (from Sonigo et al. 2011) within the identified clusters. The bars illustrate the average performance of countries in each cluster, facilitating comparisons of how different groups prioritize and implement IAS prevention measures. Country codes are: Austria (AT), Belgium (BE), Bulgaria (BG), Cyprus (CY), Czechia (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (GR), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), and United Kingdom (UK)

Figure 3. Current EAS and policy status. Number of established alien species (EAS) of seven taxonomic groups in the European Union countries and the United Kingdom. Further, the level of implementing IAS management measures is shown in four categories (i.e. fully implemented, partially implemented, similar measures implemented, not implemented; based on Sonigo et al. 2011) as pie-charts. Non-EU countries are gray in the map.

Figure 4. Models scheme. Schematic representation of the three analyzed models (rows) based on the inclusion of various response variables, management variables, covariates, and indicating whether annual analysis is conducted (columns).

Table 1. Model results

	TOTAL INVASIONS		RECENT INVASIONS		RATE-CHANGE	
Response variable	all EAS		EAS after 1995		EAS after 1995	
Historic invasions	not included		not included		included	
	Estimate	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Distance *ij*	-0.029	0.279	0.003	0.919	0.022	0.408
Climatic distance *ij*	**-0.093**	**0.001****	-0.036	0.265	0.001	0.978
Sampling effort *ij*	0.104	0.267	0.117	0.063	0.068	0.103
Trade *i* to *j*	**0.210**	**< 0.001*****	**0.186**	**0.001****	**0.115**	**0.018***
Population density *j*	-0.537	0.129	0.016	0.933	0.242	0.058
Protected area *j*	0.682	0.239	-0.007	0.983	-0.289	0.158
Country size *j*	**-0.795**	**0.044***	**-0.492**	**0.027***	-0.170	0.211
Total management *j*	0.329	0.394	-0.176	0.413	**-0.322**	**0.025***
EAS before 1995 *j*	-	-	-	-	**0.417**	**< 0.001*****

Table 2. Model results with policy clustering.

	TOTAL INVASIONS		**RECENT INVASIONS**		**RATE-CHANGE**	
Response variable	all EAS		EAS after 1995		EAS after 1995	
Historic invasions	not included		not included		included	
	Estimate	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Distance *ij*	-0,029	0,275	0,003	0,918	0,022	0,413
Climatic distance *ij*	**-0,092**	**0,001****	-0,034	0,290	0,001	0,982
Sampling effort *ij*	0,112	0,230	0,114	0,069	0,065	0,120
Trade *i* to *j*	**0,211**	**< 0,001*****	**0,189**	**0,001****	**0,118**	**0,016****
Population density *j*	-0,481	0,103	0,013	0,941	0,212	0,121
Protected area *j*	0,517	0,290	-0,058	0,847	-0,270	0,235
Country size *j*	**-0,791**	**0,020**	**-0,492**	**0,022***	-0,176	0,243
Clus. Prevention *j*	**1,566**	**0,014***	0,536	0,156	-0,105	0,701
Clus. Early warning *j*	0,505	0,413	-0,070	0,855	-0,294	0,306
Clus. Control & restoration *j*	-1,286	0,140	-1,010	0,071	-0,503	0,209
EAS before 1995 *j*	-	-	-	-	**0,414**	**< 0,001*****

Figure 1. Annual variations analysis.

Figure 2. Clustering of IAS management policies.

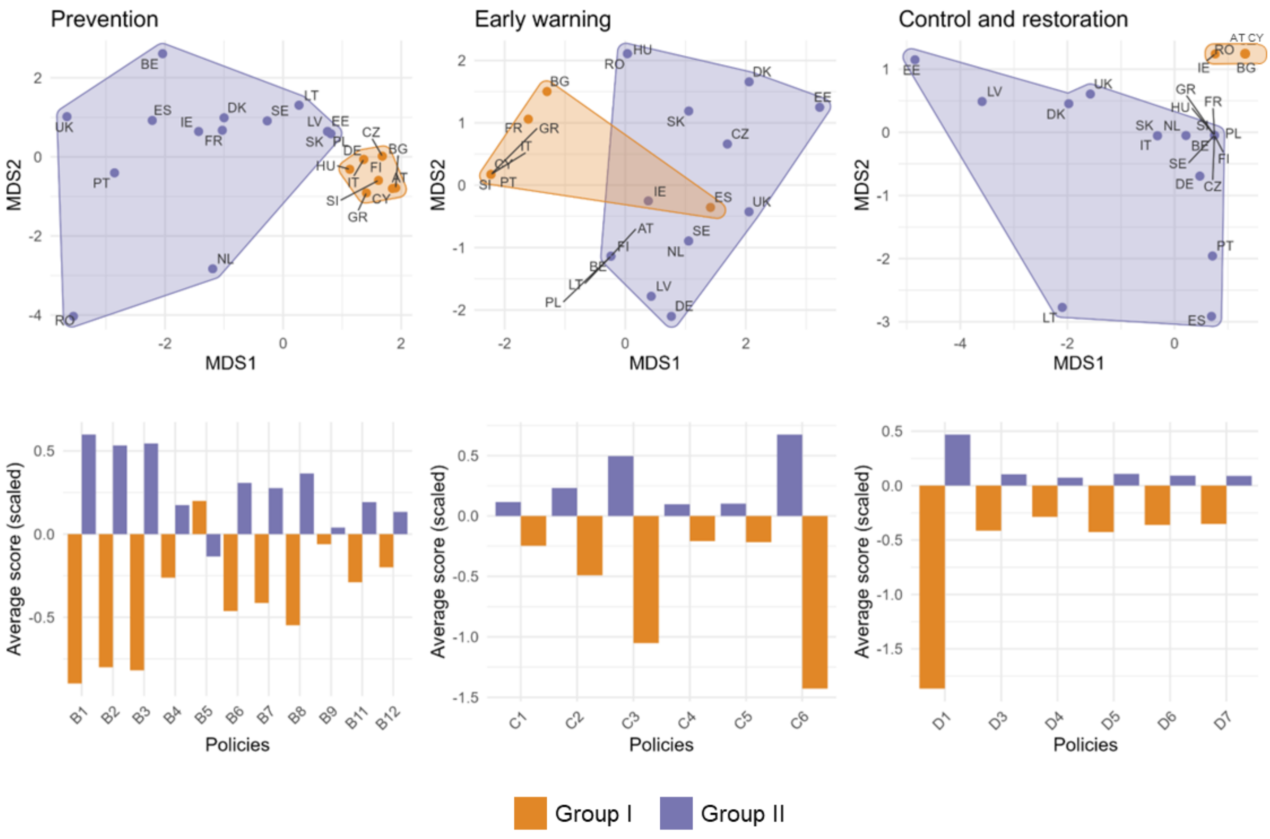

Figure 3. Current EAS and policy status

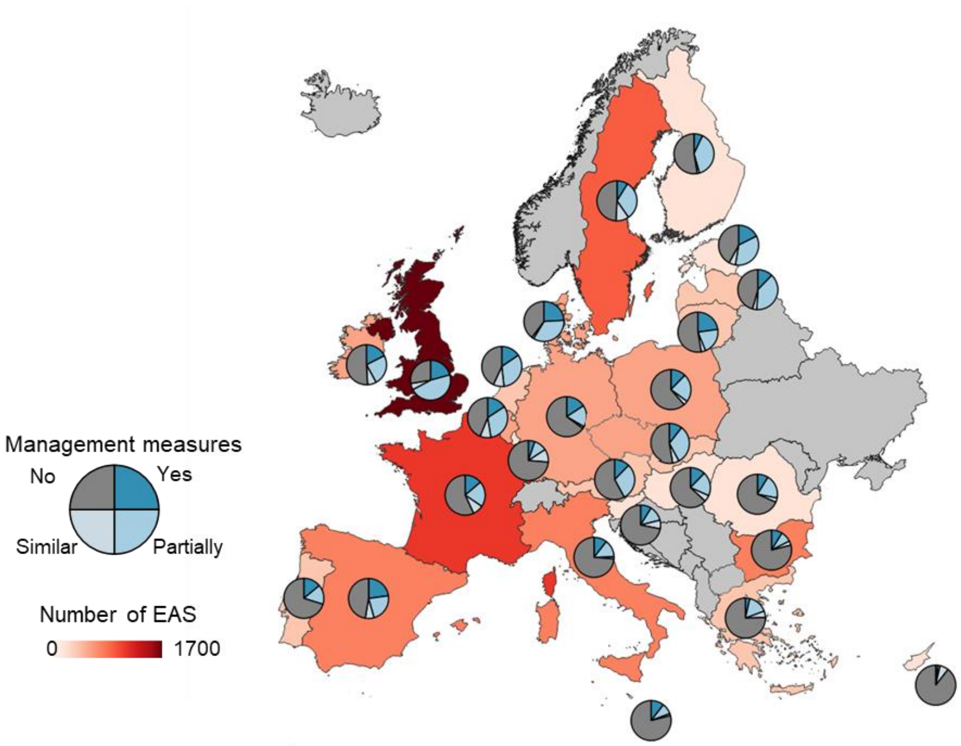

Figure 4. Models scheme.