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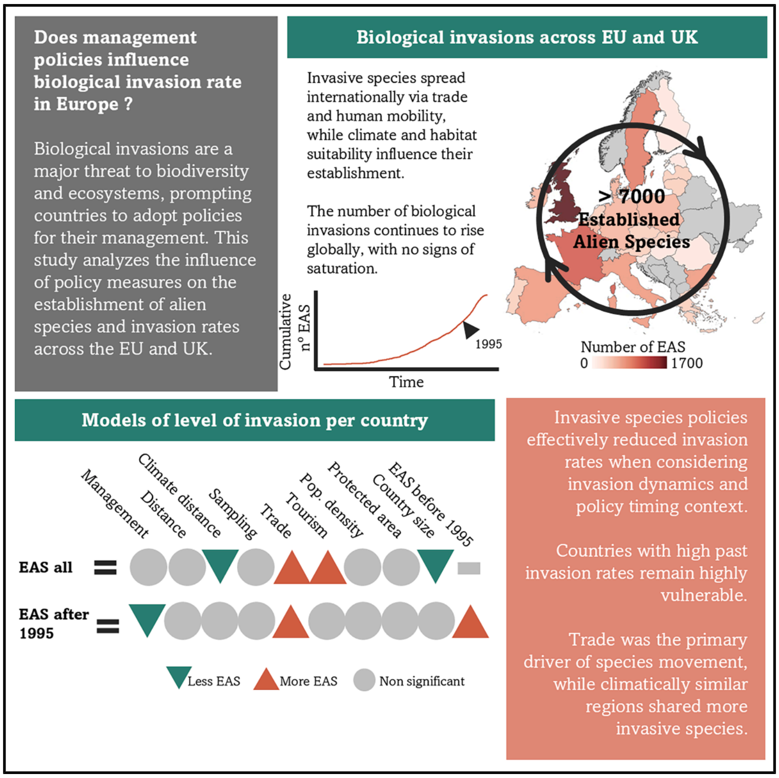
Policies slow biological invasions in Europe, but legacies still matter

Graphical abstract



Highlights

- Invasion rates in Europe declined with national IAS policy implementation
- Accounting for background invasion rates was needed to show policy effects on invasion trends
- Historical invasion levels strongly predict new introductions
- Trade remains a major driver of alien species spread

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In brief

National policies across European Union countries and the United Kingdom have slowed biological invasions, especially when accounting for invasion dynamics and policy timing. Yet, historical invasion levels remain the strongest predictor of new invasions, suggesting persistent national vulnerabilities. This study underscores the need for long-term, adaptive, and coordinated strategies to effectively manage invasive alien species and achieve global biodiversity targets.

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Policies slow biological invasions in Europe, but legacies still matter

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SCIENCE FOR SOCIETY Invasive alien species threaten ecosystems, economies, and human well-being worldwide. Governments have responded by developing policies to prevent and control these invasions. However, the effectiveness of these policies remains uncertain, partly because invasions accumulate over long timescales and depend on complex, context-specific factors. In this study, we assessed the effectiveness of invasive species policies across European Union countries and the United Kingdom by accounting for both invasion timing and policy implementation. We found that policies implemented at the national level aiming to prevent and control invasions have successfully reduced the rate of new species establishments—especially when considering policy timing and long-term invasion trends. Still, a country's historical invasion level (e.g., the number of invasive species already present in a country) was the strongest predictor of new invasions, suggesting that legacies continue to shape present-day risks. These results emphasize the need for adaptive and long-term strategies that not only respond to current threats but also address deeper, structural drivers of invasions. Our work supports ongoing efforts to meet international biodiversity goals, such as reducing the impact of invasive species by 50% by 2030.

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SUMMARY

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 sampling effort and invasion timing, across European Union (EU) countries and the United Kingdom (UK) with the number and types of policies implemented. Policy effects were analyzed alongside other invasion drivers, including trade, 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 evident only 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.

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 (species that establish self-sustaining alien populations in invaded regions; EAS hereafter) and invasive alien species (EAS causing negative ecological or socioeconomic 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 all may not be equally protective, and their capacity to prevent invasions may depend on the environmental context and legal or socioecological 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, 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 depend not only on current policies but also on legacies of historical socioeconomic 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.

Here, we evaluate the effectiveness of invasive species management policies across European Union (EU) countries and the United Kingdom. We compiled data on the similarity in invasive species composition between countries and examined their relationship with the number and types of management policies implemented in each country.[31,32] We also accounted for other drivers such as geographical factors, trade, 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 to historical invasions, or inverse, indicating a low number of invasions as a consequence of protective policies. Accordingly, we hypothesize that the direction of this relationship will depend on whether we consider recent or historical invasions. Thus, we analyzed three key metrics: the total number of EAS, the number of recent invasions (defined as those occurring after 1995), and the changes in invasion rates, defined as the number of recent invasions relative to historical ones. We found that national management policies were significantly associated with lower rates of recent invasions when examining changes in invasion rates, but policy effects were missed when only looking at absolute numbers of invasions. However, countries with historically high invasion levels remained more vulnerable regardless of policy efforts, highlighting the importance of considering invasion dynamics and policy timing. More broadly, our results support the continued implementation of targeted, adaptive policies and the need to address legacy effects in biodiversity management.

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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*	Estimate	*p*	Estimate	*p*
Distance *ij*	−0.044	0.100	−0.005	0.865	0.023	0.403
Climatic distance *ij*	**–0.088**	**0.002****	−0.033	0.307	0.001	0.979
Sampling effort *ij*	0.105	0.222	0.116	0.053	0.068	0.105
Tourism *i* to *j*	**0.118**	**0.001****	0.074	0.051	0.005	0.889
Trade *i* to *j*	**0.127**	**0.032***	**0.139**	**0.025***	**0.118**	**0.024***
Population density *j*	−0.526	0.126	0.022	0.907	0.242	0.057
Protected area *j*	0.695	0.217	0.001	0.996	−0.291	0.156
Country size *j*	**–0.791**	**0.038***	**–0.492**	**0.025***	−0.168	0.214
Total management *j*	0.334	0.373	−0.173	0.415	**–0.323**	**0.024***
EAS before 1995 *j*	–	–	–	–	**0.419**	**<0.001*****

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 boldface type.
0.05 * 0.01 ** 0.001 *** 0.

RESULTS

Relationships between EAS and total management

The variable “total management” did not exhibit a significant association with absolute numbers of “directional EAS” (EAS moving from invaded to uninvaded countries), regardless of the time of introduction (i.e., the total and the recent invasions models, see 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 policy 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 cutoff years, from 1995 to 2000 (Figure 1).

Regarding the other predictors, in the total invasions model, trade, and tourism between countries were significant and positively associated with directional EAS, indicating that higher levels of trade and tourism between countries corresponded to an increased number of established species (Table 1). Country size and climatic distance displayed an inverse relationship with 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 1995–1997 (Figure 1). Sampling effort also presented some significance to directional EAS for 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 to 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 2B).

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 a higher count of directional EAS (Figure 1; Table 2). However, the effect of individual policy clusters was not detectable for the recent and rate change models (Figure 1; Table 2).

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

DISCUSSION

The importance of IAS management policies on EAS

Our analysis examined the effect of IAS management policies on the terrestrial directional EAS count between pairs of countries in the EU and the United Kingdom. The results show that total management (indicating the total number of actions taken by countries' policies regarding the management of biological invasions) was negatively associated with the rate of new invasions experienced by each country. However, the lack of significance in the recent invasions model (that uses absolute

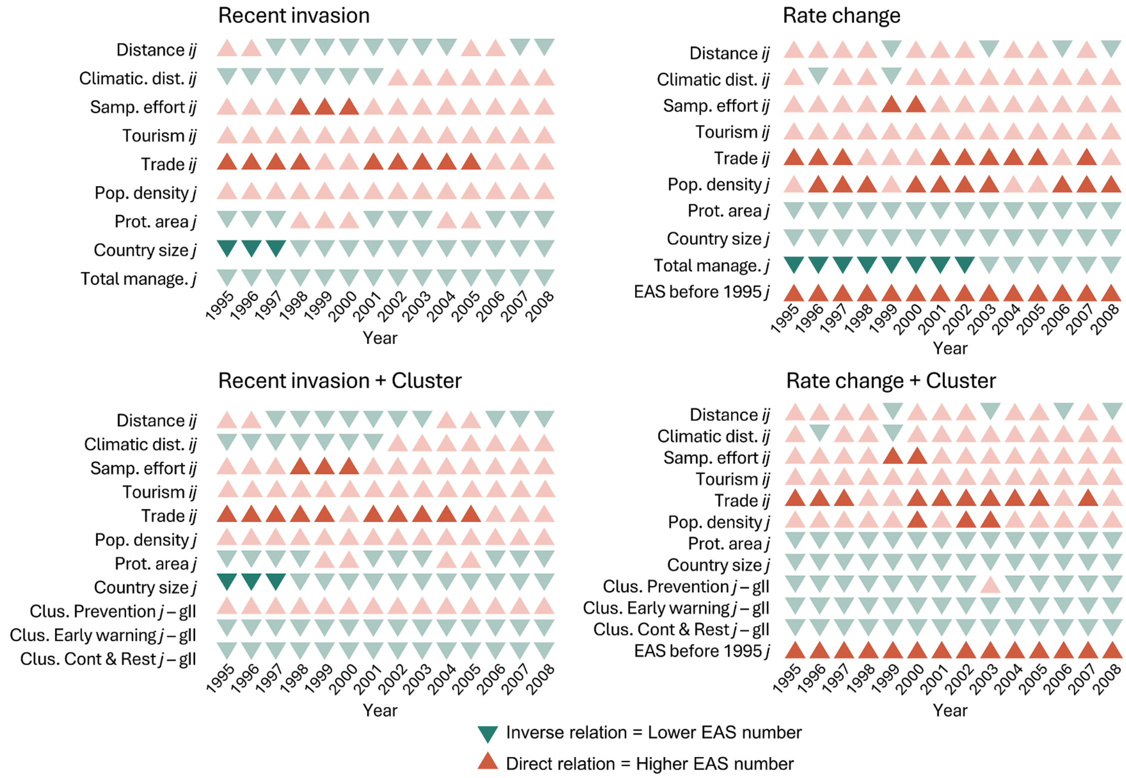

Figure 1. Annual variations analysis

Annual variations analysis between the years 1995 and 2008 for the recent invasions and rate change models. (Top) The relationships for the models using total management; (bottom) the relationships for the models using management policy types within the clusters. Red indicates direct relationships between the number of established alien species (EAS) and the predictor variables, while green indicates inverse relationships. Significant relationships ($p < 0.05$) are indicated in dark colors and non-significant relationships are indicated in light colors.

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,[34] 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, then management policies may only partially counterbalance these added risks. Consequently, the rate change model, which accounts for historical trends between countries, proved to be the most sensitive in detecting the impact of management efforts on invasions.

Furthermore, our analysis reveals that historic invasions remained the strongest predictor of recent invasions. Countries with a higher number of EAS prior to the cutoff year of 1995 also tend to have more new EAS in the recent period considered. This indicates that countries historically more susceptible to invasions continue to face high vulnerability to EAS, suggesting that the same underlying drivers of past introduction rates still shape current invasion dynamics.[9–12,35] Our findings underscore the enduring influence of historical legacies and highlight the persisting challenges of tackling biological invasions, even as recent regulations and management efforts begin to curb the invasion tide.

Our analyses show that the ability to detect the influence of management policies diminishes after 2000, despite increases in the legislative corpus over this period. This result could seem counterintuitive at first; however, the challenge of detecting policy effects on recent EAS is likely exacerbated by known time lags in biological invasions.[36] These lags include both reporting delays, defined as the time needed to record a new EAS and include it in the related databases, and the time required for the species to spread and become detectable at broader spatial or ecological scales.[36] In addition to these biological and observational delays, statistical power is considerably reduced in the post-2000 period, which only accounts for approximately 10% of all first records in our dataset. This limited sample size makes it more difficult to detect consistent trends, even if such trends exist. Consequently, drawing conclusions about recent patterns remains challenging.

Finally, cluster analyses categorized countries based on various types of alien species management policies, revealing

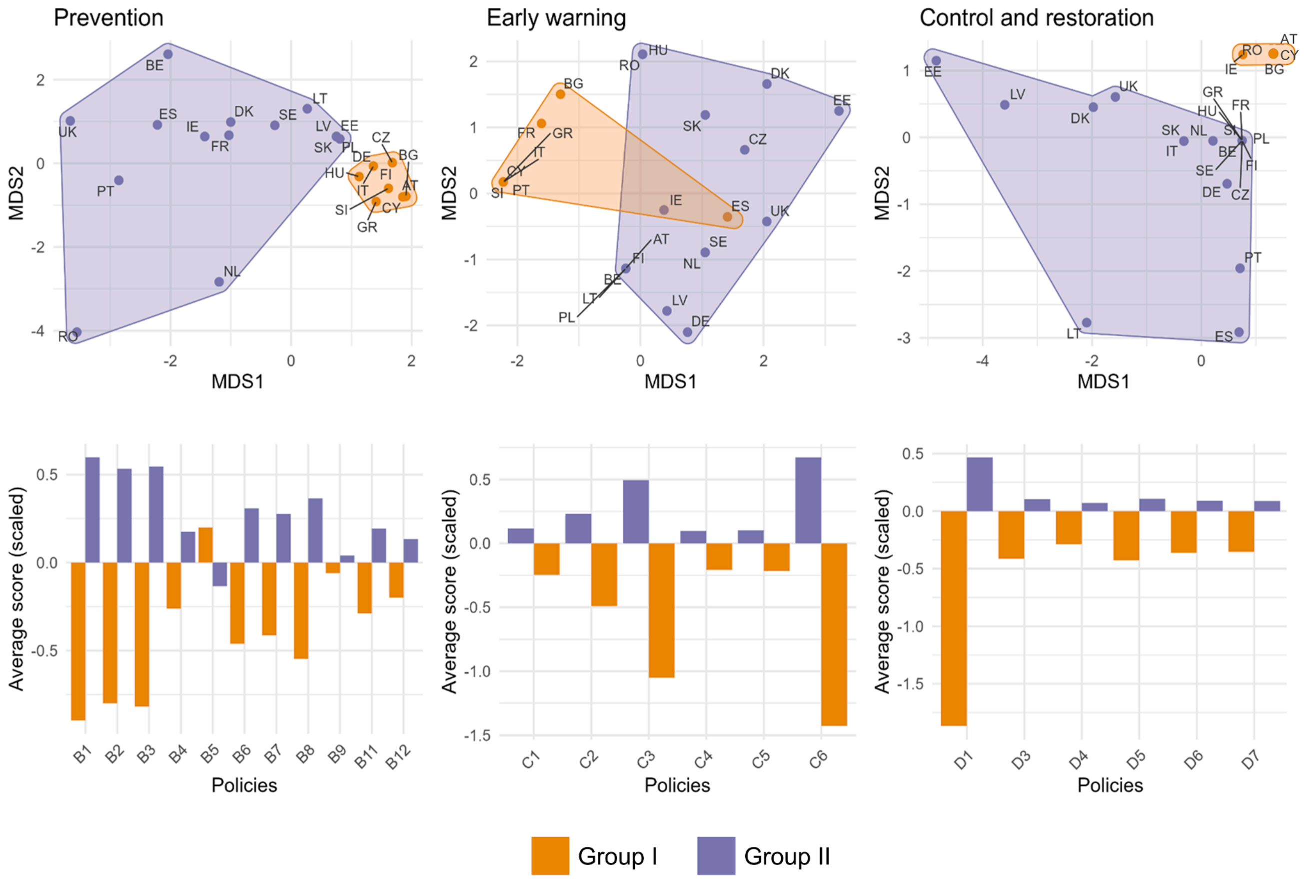

Figure 2. Clustering of IAS management policies

Cluster results of the European Union (EU) countries and the United Kingdom based on their implementation of three types of invasive alien species (IAS) policies. (Top) Categorization of 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. (Bottom) The average normalized scores for each policy type (see Table S1; data from Sonigo et al.[33]) 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: 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).

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,[37,38] 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 preventive management policies.

The influence of other covariables

Across all models, trade activity among pairs of countries (i.e., import values) emerged as a primary driver directly associated with the number of directional EAS here studied. This finding aligns with previous studies demonstrating that international trade increases the likelihood of introducing alien species as stowaways or traded organisms.[11,12,39] By examining trade dynamics between pairs of countries rather than merely considering total import volumes, we can analyze a more nuanced understanding of potential introduction pathways. Importantly, trade remained important and positive in the rate change model.

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, while tourism was directly related to it in total invasions models. In other words, regions with high flow through major transport routes (specifically air travel in this study) and that are more ecologically similar tend to share more EAS. This confirms the relevance of species' ecological requirements for establishment.[29] However, these relationships were not observed in the recent invasions or rate change models, possibly because of fewer invasions and lower power (in the recent invasion model) and a consistent effect (no change in rate in the rate change model). In contrast, an inverse relationship between country

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*	Estimate	*p*	Estimate	*p*
Distance *ij*	−0.045	0.096	−0.005	0.867	0.022	0.414
Climatic distance *ij*	**−0.087**	**0.003****	−0.031	0.334	0.001	0.981
Sampling effort *ij*	0.112	0.189	0.113	0.059	0.065	0.121
Tourism *i* to *j*	**0.119**	**0.001****	0.074	0.052	0.002	0.954
Trade *i* to *j*	**0.127**	**0.033***	**0.142**	**0.022***	**0.119**	**0.023***
Population density *j*	−0.469	0.097	0.019	0.914	0.212	0.121
Protected area *j*	0.534	0.255	−0.048	0.872	−0.271	0.235
Country size *j*	**−0.790**	**0.016***	**−0.493**	**0.020***	−0.175	0.246
Cluster prevention *j*	**−1.568**	**0.011***	−0.538	0.148	0.106	0.699
Cluster early warning *j*	−0.483	0.413	0.084	0.824	0.294	0.306
Cluster control and restoration *j*	1.256	0.133	0.992	0.072	0.503	0.209
EAS before 1995 *j*	–	–	–	–	**0.414**	**<0.001*****

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 boldface type.
0.05 * 0.01 ** 0.001 *** 0.

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 pattern may result from multiple interacting factors, including geographical proximity, or even the interaction of trade volume and country size. For instance, countries like Belgium, the Netherlands, Czechia, and Austria, despite their relatively small size, may experience high EAS arrivals due to intense international trade pressure and their central location in Europe, which increases flow with multiple neighboring countries. The current models do not account for cumulative propagule pressure, which would require a more mechanistic approach.[40] Sampling effort was directly related to the directional EAS number detected, as previously described.[41] 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.[42]

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,[43,44] resulting in a global increase in alien species richness.[6] Our analysis also confirmed that climatic distance has a significant effect on dispersal patterns of terrestrial EAS between countries. Notably, the impacts of climate change vary across geographic regions and taxonomic groups, further shaping these movements. In the context of accelerating climate change, these trends will likely exacerbate the impacts of biological invasions on native biodiversity.[45] Several modeling studies have projected an expansion of climatic suitability for alien species in Europe under climate change,[46–48,49] and rising establishment rates have been directly linked to climate change, even when controlling for propagule pressure.[45]

The relationship between invasive species numbers and country-specific factors, such as trade volume and gross domestic product, is well documented.[9,21,50] However, invasions are dynamic processes shaped by specific historic and socioeconomic relationships between countries. Understanding EAS flows requires an analysis that goes beyond individual country traits to examine species spread from one country to another.[17,39] A more mechanistic approach, explicitly modeling 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.

It is important to note that our study focuses exclusively on terrestrial EAS, excluding aquatic species such as fish, crustaceans, or mollusks, due to lack of equally reliable expert-curated data for these groups. While patterns observed in terrestrial EAS provide valuable insights into the broader dynamics of biological invasions, aquatic EAS often involve different introduction pathways and management challenges. Our study is based on the integration of multiple expert-curated databases, which ensures a high level of comprehensiveness and reliability. However, these data may still be affected by uneven reporting efforts between countries and taxonomic groups. The inclusion of a sampling effort variable enables us to control for cross-country differences in biodiversity data completeness and reporting capacity, helping reduce potential biases in our analyses. Despite these limitations, the significant effects detected, such as those of trade, past invasions, and management—are unlikely to be artifacts of data noise alone, indicating robust patterns. Regarding countries' management policies, the database compiled by Sonigo et al.,[33] although the most comprehensive and validated source available, does not ensure full consistency in the inclusion of all measures across countries. Furthermore, since 2014, EU Regulation 1143/2014 has established a more standardized framework across member states, including periodic reporting obligations (with the first reporting period covering 2015–2018). Nevertheless, the effectiveness of these regulations cannot yet be fully evaluated due to the temporal lags discussed above.

While previous studies have evaluated management strategies regionally[51] or through stakeholder perceptions,[52,53] this work represents the first direct assessment of the impact of IAS management policies on a country scale in Europe. Our findings confirm that EU management policies can indeed slow down the rate of terrestrial 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 refined further. 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 policy development and its 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 multiscale 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. 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, further research should aim to assess the impact of the 2014 IAS regulation and other recent measures as more data become available and to extend the analytical framework to include other underrepresented taxonomic groups. We hope our study provides a foundation to support such future assessments and the continued development of evidence-based policy.

Conclusions

This study provides evidence that alien species management policies at a national scale across EU countries and the United Kingdom have significantly reduced invasion rates for multiple taxonomic groups, particularly when considering changes over time. Our findings highlight the persistent influence of historic invasions, which have remained the strongest predictor of new invasions. This suggests that some countries may be consistently more prone to biological invasions due to enduring national characteristics that have shaped invasion levels in the past. Thus, there is an urgent need for policies not only addressing current invasion drivers but also structural vulnerabilities to invasion. Strengthening and adapting management measures, such as enhancing cross-border coordination and policy coherence, may help to improve their effectiveness. Regulation (EU) 1143/2014 provides a framework for coordinated actions across countries, aiming to harmonize efforts. Although it may be too early to fully assess its long-term impact, periodic reassessments (e.g., each decade) will be essential for evaluating its effectiveness. By doing so, management policies could help to achieve the Kunming-Montreal Global Biodiversity Framework goal that aims to reduce by at least 50% the impacts of IAS on biodiversity and ecosystem services by 2030.

METHODS

Data on EAS

We obtained EAS richness (Figure 3) for 28 European countries—the EU member states and the United Kingdom—for seven taxonomic groups for which country-level data were available: vascular plants,[54] ants,[55] birds,[56] mammal,[57] spiders (W. Nentwig, personal communication), amphibians, and reptiles.[58] The consideration of these taxa and the lack of aquatic species relies on data availability from expert collaborators, ensuring data reliability. We obtained additional data for all groups from the Global Alien Species First Record Database, version 3.1.[59] 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 6,667 species (6,271 vascular plants, 134 ants, 105 birds, 58 mammals, 50 spiders, and 49 herptiles). Details about data treatment are provided in Note S1, and a complete list with the considered species is available at Canelles et al.[60]

Management variables

We obtained information on countries' management policies from Sonigo et al.,[33] 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 (see Figure S1 and Table S1). 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 Table S1). Each criterion was classified by Sonigo et al.[33] 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

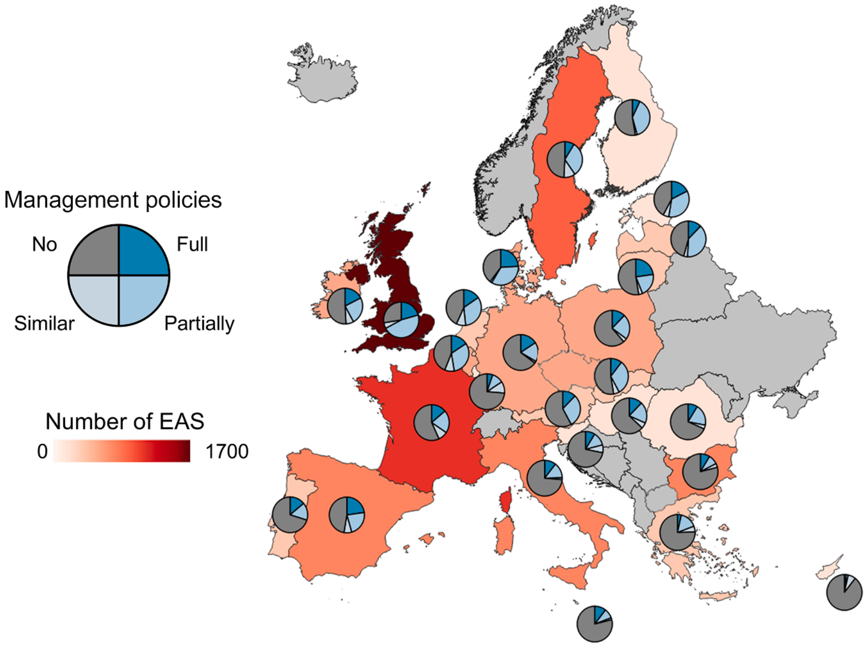

Figure 3. Current EAS and policy status
Number of EAS of seven taxonomic groups in the EU countries and the United Kingdom. The level of implementing IAS management measures is shown in four categories (fully implemented, partially implemented, similar measures implemented, not fulfilled; based on Sonigo et al.[33]), and pie charts indicate the distribution of policy implementation levels per country. Non-EU countries are gray on the map.

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: (1) prevention, (2) early warning, and (3) control and restoration. Specifically, we calculated a 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, which 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[61] for the cluster analysis.[62]

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.

(1) Geographical data: for each country, we extracted country size (km2), and the percentage of terrestrial protected area for the year 2020 from the World Bank Data[63] and from the World Database on Protected Areas.[64] Finally, the spatial distance between countries was calculated as the minimum great-circle distance in radians between the borders of two countries.
(2) Socioeconomic data: for each country, we extracted human population density (inhabitants/km2), the average import values for each country from 1995 to 2018 using the Open Trade Statistics,[65] and the average number of air passengers for each country for the same period from EuroStats,[66] as a surrogate of tourism.
(3) 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[67] at a 10-min 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.
(4) Sampling effort: this index, extracted from Dawson et al.[41] and based on Meyer et al.,[68,69] represents the mean percentage of completeness of native species inventories for different taxa calculated at a 110 × 110-km resolution for each country. It was calculated based on the number of Global Biodiversity Information Facility[70] 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, referred to as directional EAS. Doing so enabled us to describe the invasion patterns within the EU and the United Kingdom, where EAS spread from invaded (i) to uninvaded countries (j).[71] The first occurrence of a species in the EU and the United Kingdom was excluded from these analyses, as it does not represent secondary spread.

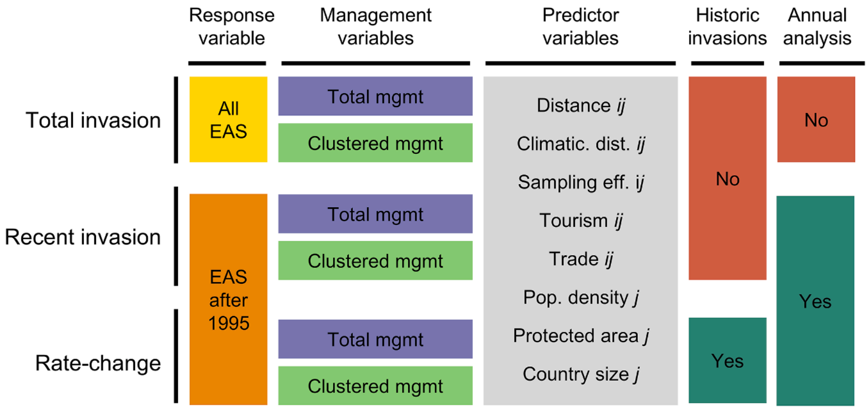

Figure 4. Models scheme
Conceptual scheme of the three analyzed models (rows) based on the inclusion of various response variables, management variables, and covariates and indicating whether annual analysis is conducted (columns).

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 Global Alien Species First Record Database.[59] 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 (see Equation 1).

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

(1) 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 BCE to 2020). We modeled the relationship between the response variable directional EAS and the explanatory variable total management of the recipient country (*j*) (see Equation 1). In addition, we included the following pair-specific covariables: trade between countries, number of tourists 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 their 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.

(2) Recent invasions: this model considers as the 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.,[33] 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.[72] We identified the year of first detection of alien species in each country using the First Record Database.[59] 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.

(3) 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 covariates 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. This is detailed in Figure S2 and Table S2.

The notation of the models is as follows:

$$Y_{i,j} \sim M_j + T_{i,j} + TO_{i,j} + D_{i,j} + C_{i,j} + S_{i,j} + P_j + PA_j + SA_j + (1|i) + (1|j), \quad \text{(Equation 1)}$$

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*, *TO* was tourism from *i* to *j, D* was the distance between *i* and *j*, *C* was climatic distance between *i* and *j*, *S* was the sum of the sampling effort in *i* and *j*, *P* was the population size in *j*, *PA* was the protected area in *j*, *SA* was the 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 modeling rate change did we incorporate Yb1995, which was the directional EAS recorded before 1995 in *j*.

Each response variable and 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*[73] in R 4.1.0,[61] 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 1995–2008, as more recent EAS data may be incomplete due to time lags between species establishment and detection.[36] Additionally, we repeated the same tests for each of the three following taxonomic groups: invertebrates, vertebrates, and plants. The results and a short discussion of the taxonomic analysis are included in Figure S3.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Quim Canelles (quimcanellestrabal@gmail.com) .

Materials availability

No new materials were generated.

Data and code availability

The R code and dataset used in this manuscript is available at Zenodo: https://doi.org/10.5281/zenodo.15495043. Further information and requests for resources should be directed to the lead contact, Dr. Q. Canelles.

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AUTHOR CONTRIBUTIONS

Q.C., C.P.-G., N.R.-P., and B.L. 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.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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