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Prioritizing management actions for invasive non-native plants through expert-based knowledge and species distribution models

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ABSTRACT

Given the high number of non-native plants that are being introduced worldwide and the time required to process formal pest risk analyses, a framework for the prioritization of management actions is urgently required.

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Eradication
Management priorities
Prioritization scheme

We therefore propose a framework for a replicable and standardized prioritization for management actions (eradication, control and monitoring) of invasive non-native plants, combining expert knowledge, current and future climatic suitability estimated by species distribution models (SDMs), clustering and ordination techniques. Based on expert consultation and using Italy as case study, invasive non-native plant species were selected and three categories of management actions were identified: eradication, control and containment, and monitoring. Finally, two further classes of priorities were proposed for each of the management actions: "high" and "low" priority. Overall, SDMs highlighted a high and very high suitability for Continental and Mediterranean bioregions for most invasive plants. Cluster analysis revealed three distinct clusters with varying levels of suitability for the Italian bioregions. Cluster 1 exhibited a higher suitability across all Italian bioregions, whereas non-native plants grouped in Cluster 2 predominantly featured high suitability in Mediterranean areas. Finally, Cluster 3 showed the lowest suitability values. Two ordination analysis highlighted the variability in bioclimatic suitability for each non-native plant within each cluster, as well as their current distribution pattern. Lastly, a third ordination, integrating bioclimatic suitability and spatial patterns, has allowed the differentiation of management actions for each non-native plant at both national and bioregional scales. Specifically, seven non-native plants were earmarked for eradication action, six for monitoring action, while the remaining species were deemed suitable for control and containment. Our results and the methodology proposed meet the demand for replicable new early warning tools; that is to predict the location of new outbreaks, to establish priorities for eradication, control and containment, and to monitor invasive non-native species.

1. Introduction

Invasive non-native species pose great challenges to nature conservation and ecosystem functioning (Roy et al., 2023). At the same time, newly established invasive species are rapidly increasing at the global level (Seebens et al., 2017, 2018, 2021) with most of the countries in the world featuring high numbers of naturalized non-native plants (Pyšek et al., 2017). Prioritization is of paramount importance for the management of biological invasions, as recognized by a vast corpus of scientific literature (e.g., McGeoch et al., 2016; Booy et al., 2020) and by several principles and international commitments within the framework of the Convention on Biological Diversity. For example, the Kunming-Montreal Global Biodiversity Framework, Target 6, call upon countries to pledge to " … eliminate, minimize, reduce and/or mitigate the impacts of invasive alien species on biodiversity and ecosystem services by identifying and managing pathways of the introduction of alien species, preventing the introduction and establishment of priority invasive alien species, reducing the rates of introduction and establishment of other known or potential invasive alien species by at least 50 per cent by 2030, and eradicating or controlling invasive alien species, especially in priority sites, such as islands" (Convention on Biological Diversity, 2022a). Furthermore, IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Roy et al., 2023) and European legislation (e.g., Regulation (EU) no. 1143/2014) are taking it upon themselves to find countermeasures to biological invasions in order to control or eradicate priority species, and to manage pathways to prevent the introduction and establishment of new invasive non-native species.

Presently, management delays often emanate from a lack of monetary rationale to invest at early invasion stages, which precludes effective prevention and eradication (Ahmed et al., 2022; Henry et al., 2023). However, the CDB and EU policy commitments and the decisions to be taken can be supported by standard and replicable methods implemented at different scales to achieve early detection, mapping, and monitoring, of invasive non-native plants, as well as to assist prioritization to optimize the use of available funding. There exists a plethora of prioritization methods, with many of them tailored to specific contexts (e.g., Potgieter et al., 2022) or species (e.g., see Forner et al., 2022, for a review) and with different sets of criteria, tools, and strategies for involving stakeholders (e.g., Forsyth et al., 2012). In this framework, modelling techniques such as species distribution models (SDMs) are recognized as efficient and replicable tools to predict the potential distribution of invasive non-native species and they can support most of the typical management actions for tackling plant invasions (e.g., Vicente et al., 2013; Lazzaro et al., 2016; Chapman et al., 2019; Sofaer et al., 2019, Davis et al., 2024) including prioritization (Branquart et al., 2016; Tanner et al., 2017). The use of SDMs is a good approach to recognize areas at high risk of invasion by well-known invasive species (Fournier et al., 2019). Moreover, SDMs can be used to identify the most relevant factors promoting plant invasions in specific types of habitats or land-uses, e.g., in protected areas, and across different biogeographical regions (e.g., Bazzichetto et al., 2018; El-Barougy et al., 2021; Lozano et al., 2023). Additionally, SDMs have been used to highlight places that have not yet been invaded or that are in the first stages of invasion, but for which the model predicts a high invasion risk in the near future and for which actions and resource allocation should be a priority (Vicente et al., 2013; Bazzichetto et al., 2018).

Plant invasion processes in Italy follow the global increasing trend highlighted above, so that new non-native species are continuously recorded within the national territory (Galasso et al., 2024), with rapidly increasing numbers of naturalized and invasive species (e.g., Celesti-Grapow and Blasi, 2004; Celesti-Grapow et al., 2009, 2010, 2016; Lazzaro et al., 2020; Lozano et al., 2020, 2023). However, so far, prioritization methods have been applied only in a few Italian study cases, mainly on islands (e.g., Lazzaro et al., 2016; Fois et al., 2020; Cossu et al., 2022). These national prioritization attempts were based on the EPPO (European and Mediterranean Plant Protection Organization) Prioritization Process (EPP; Brunel et al., 2010) and on the Australian Weed Risk Assessment scheme (A-WRA; Pheloung et al., 1999).

In this context, focusing on Italy as a case study, the aim of this research was twofold: (i) to identify and deliver to the EPPO a list of non-native invasive plants not yet regulated in Italy and not yet included in the EPPO prioritization and listing system; (ii) to prioritize management actions for such a group of non-native invasive plants. A list produced by expert elicitation was therefore analyzed with a novel methodology by combining Species Distribution Models (SDMs, i.e., assessing potential climatic suitability), clustering and ordination techniques. The applied methodology is designed to identify the highest priority for management without considering the different mechanisms and intensity of the impacts of the assessed species, to give the possibility to run a prioritization also in the lack of sound information on potential and actual impacts (Canessa et al., 2021). However, impact assessment (or other criteria) can be applied to further discriminate within the species included by the method in the same management type or management scale.

2. Material and methods

2.1. Expert consultation for data collection on invasive non-native species

A working group composed of members of the Italian Botanical Society (SBI, https://www.societabotanicaitaliana.it/) identified not regulated in Italy and in some cases emergent invasive non-native plants across all the Italian administrative regions (Fig. 1A) and provided data on these species. Data collection criteria included: (1) non-native plant species showing at least one established population in Italy and not yet included in the Union list (*sensu* EU Regulation no.1143/2014) and not regulated in Italy at a national level; (2) non-native species with potential invasive behavior already reported in countries with comparable climates and land uses; (3) non-native species with recognized impacts on biodiversity in Italy (at least on an expert basis); and (4) non-native species not yet included in any of the EPPO lists (e.g., A1/A2 Lists, List of IAP, Observation List and Alert List,).

For each proposed species, the experts were asked to provide data on

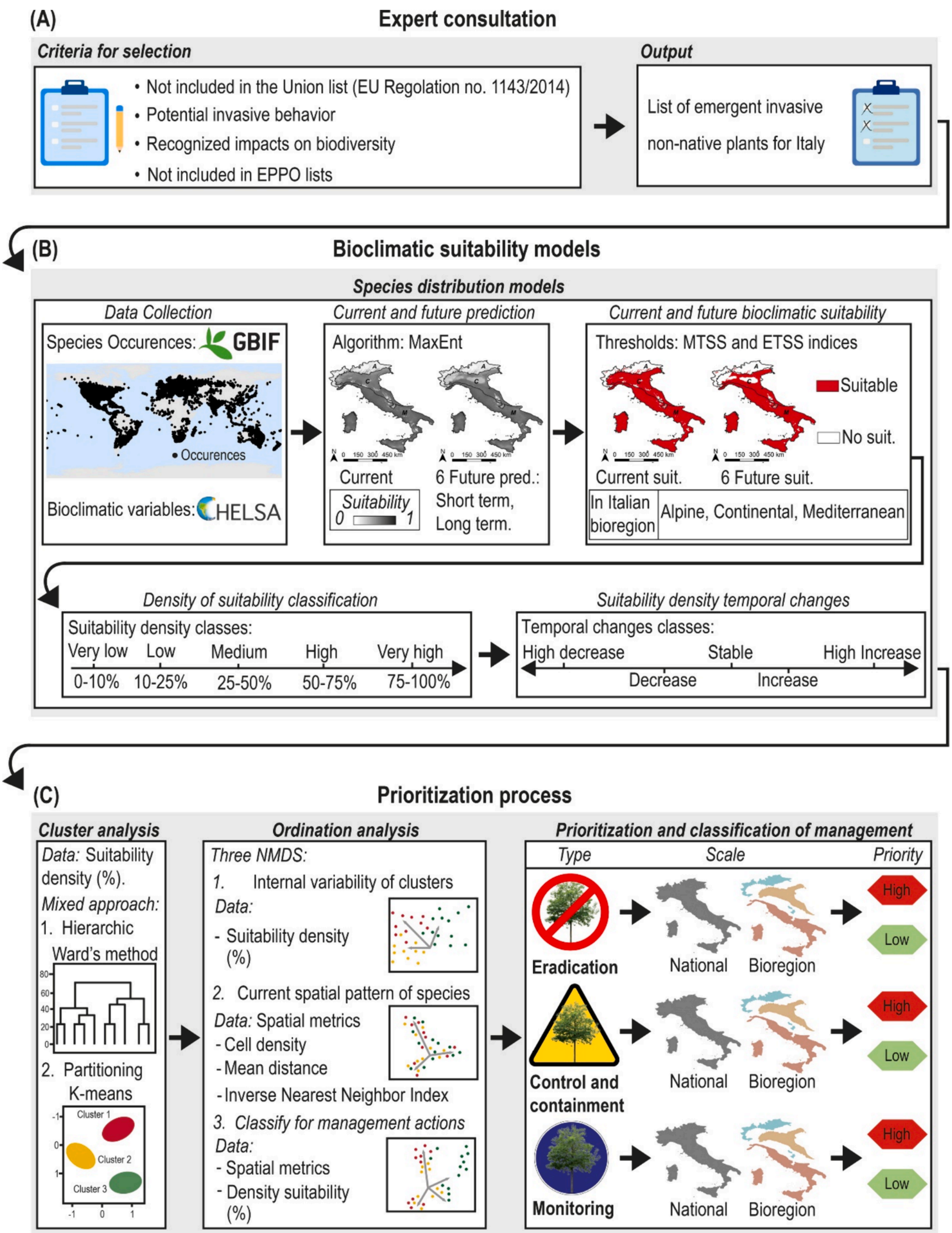

Fig. 1. Schematic overview of the conceptual framework applied to prioritize management actions for invasive non-native plants through expert-based knowledge and Species Distribution Models.

a) the native range (retrieved according to the Plants of the World Online, POWO), b) the distribution in the EPPO region, c) information on the entry pathways in Italy, d) impact mechanisms, e) impact outcomes in Italy and f) supporting data sources (i.e., scientific literature, technical reports, grey literature, or expert knowledge). The nomenclature of the non-native plants follows Galasso et al. (2018, 2024).

2.2. Bioclimatic suitability models and selection of species for modelling

We assessed potential current and future bioclimatic suitability for the invasive non-native species proposed by the SBI working group on a global scale, using species distribution models (SDMs, Fig. 1B). Bioclimatic matching models were carried out at current climate and for two future scenarios (short and long term) using three climate change scenarios based on Shared Socioeconomic Pathways (SSP), in particular SSP126, SSP370 and SSP585 (Riahi et al., 2017). Specifically, the SDMs were intended to reveal the probability of invasion for the selected invasive non-native species known to affect native plant communities on a national scale.

Current and future SDMs were performed using the Maximum Entropy (MaxEnt) algorithm at the global scale using “dismo” v. 1.3–14 R package (Hijmans et al., 2023). Although many other methods are available, MaxEnt was chosen since it is an efficient machine learning method to define a suitable area for presence-only data (Phillips et al., 2006). To predict current bioclimatic suitability, models were set up by randomly selecting 10,000 background points on a global scale excluding bioclimatic cells that included the presence of invasive non-native species (Hysen et al., 2022). We used a large number of background points to sample the largest number of bioclimatic combinations at the global scale (Elith et al., 2011). As no independent data existed to evaluate the predictive performance of the SDMs, we randomly sampled 75 % of the occurrences for model training and the remaining 25 % for model evaluation (Araújo and New, 2007). The performance of each SDM was assessed through the Area Under the Receiver-Operator Curve (AUC) and the Continuous Boyce Index (CBI; Hirzel et al., 2006). AUC is a standard measure for the accuracy of SDMs considering sensitivity (i.e., the proportion of occurrences correctly predicted) and specificity (proportion of absence correctly predicted). CBI estimates how much model predictive power differs from randomly expected SDM (Hirvel et al., 2006). CBI for each SDM was implemented using the function *evalContBoyce* included in the “enmSdmX” R package (Smith et al., 2023).

Species occurrences for the SDMs were retrieved from the Global Biodiversity Information Facility database (GBIF, Fig. 1B, available at: https://www.gbif.org, accessed in July 2023; the total number of geographic records used to create the models is reported in Table S1). Records with insufficient spatial accuracy (≥1000 m radius), potential errors (duplicates of the same occurrence), and records occurring in the sea were excluded, as well as records collected before 1981. To mitigate spatial autocorrelation, multiple points in the same cell were removed, and only one occurrence per cell was considered. As a result, the number of georeferenced records available for SDMs was reduced to 385,879, with an average of 4,462 records per invasive non-native plant, and the georeferenced records available for each non-native plant available for SDMs ranged from 52 to 19,301 (Table S1). However, the invasive non-native plants with less than 100 occurrences, across the native and invasive range, were not further considered in the analysis due to a potential lack of information on their climatic niche (see Table S1). In fact, Wisz et al., 2008 in their publication tested MaxEnt in the range 10–100 occurrences, highlighting a better performance of the algorithm in the range 30–100 occurrences.

2.3. Bioclimatic suitability models in the current climate and future scenarios

To calibrate the SDMs, current bioclimatic variables obtained from the CHELSA climate data set version 2.1 (https://chelsa-climate.org/, Karger et al., 2021, Fig. 1B) were used. The data set has a global extent and consists of 19 bioclimatic variables (Table S2), estimated by a downscaling approach at a high resolution (30 arc sec. ~ 1 km). The 19 bioclimatic variables are available for current climate condition in U.S. NOAA and Canadian Weather Service Normals 1981–2010.

Before computing bioclimatic suitability models, the initial climatic dataset was sub-selected by checking for multi-collinearity, i.e., posing a variance inflation factor (VIF) with a threshold of five (VIF ≥ 5, as suggested by Dormann et al., 2013) using the function *vifcor* included in the “usdm” R package (Naimi et al., 2014). As a result, the number of variables used for SDMs was on average 8 among the 19 original variables (see Table S3 for detailed information).

To calibrate the SDMs for future scenarios, we used the three Shared Socioeconomic Pathways (SSPs) produced by the Intergovernmental Panel on Climate Change (IPCC), in particular SSP126, SSP370, SSP385, for two periods 2041–2070 (Short Term) and 2071–2100 (Long Term) to include all possible global pathways (Fig. 1B, Karger et al., 2023). The SSPs in the two future projections (short and long term) are estimated from mean values of five primary general circulation models (GFDL-ESM4, UKESM1-0-LL, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0) of CMIP6 (Coupled Model Intercomparison Project Phase 6, Karger et al., 2021, 2023).

Finally, the dataset of the current climate and all SSPs for Short Term and Long Term predictions contains 133 current and future projections of 19 bioclimatic variables.

In the current and future scenarios, the logistic output of bioclimatic suitability models, obtained by the MaxEnt algorithm, was converted into binary maps composed of two classes (Fig. 1B): suitable (S) and unsuitable (US) bioclimatic conditions. The suitable bioclimatic condition was defined when the logistic output of MaxEnt was greater than two thresholds (Fig. 1B): the Maximum Training Sensitivity and Specificity logistic threshold (MTSS) and the Equal Training Sensitivity and Specificity logistic threshold (ETSS, Manel et al., 2001; Salako et al., 2019).

Then, the density of suitability cells, in each Italian biogeographical region (Alpine – A, Continental – C, and Mediterranean – M, EEA, 2016), was calculated as the number of suitable cells divided by the number of cells in each biogeographical region following the corresponding reference grid (1 km × 1 km) of the European Environmental Agency (https://www.eea.europa.eu/, Fig. 1B). The suitability density was calculated in the current bioclimatic condition and three pathways (SSP126, SSP370, SSP585) of the Short Term and Long Term scenarios. The values of density obtained were then classified into five percentage classes (%): very low (0–10 %), low (10–25 %), medium (25–50 %), high (50–75 %) and very high (75–100 %, Fig. 1B). To evaluate possible changes due to the spread of invasive non-native plants caused by climate change, the difference in suitability density among current and future bioclimatic scenarios was calculated and the difference values obtained were classified into five classes as follows: no change (±0 to 5 %), decrease (−5 to −15 %), high decrease (−15 to −100 %), increase (+5 to +15 %), high increase (+15 to +100 %, Fig. 1B).

2.4. Prioritization process of invasive non-native plants

Aiming to classify the proposed invasive non-native plants into priority classes (low and high) according to main management actions in Italy (i.e., eradication vs. control and containment, or monitoring), three hierarchical steps were performed as follows (Fig. 1C): 1) a cluster analysis to gather invasive non-native plants into homogeneous groups based on current and future climatic suitability density values; 2) a non-metric multidimensional scaling ordination analysis to evaluate the differences inside each cluster, using bioclimatic variables, and to estimate the current distribution pattern in Italy, using spatial metrics as variables and 3) a classification of invasive non-native plants into management priorities in Italy based on the results of the two previous steps.

2.4.1. Cluster analysis

The cluster analysis was performed using a mixed approach, combining hierarchic and partitioning methods (Fig. 1C). The categorization was based on 21 predictors (i.e., three variables for current bioclimatic scenarios; six variables for SSP126, six variables for SSP370 and six variables for SSP585) defined as suitability density values (%) in current and future bioclimatic scenarios for each invasive non-native plant in the three Italian biogeographical regions.

Before cluster analysis, variables were prepared as follows. Firstly, multi-collinearity among suitability density variables was calculated using Variance Inflation Factors (VIF) with a threshold of ten (VIF $\geq$ 10) to avoid redundant information (Morales-Barbero and Vega-Álvarez, 2019). Secondly, outliers below the 0.05 percentile and above the 99.5 percentile were removed using the winsorization and substituted with the respective percentile threshold (Wu and Zou, 2009). Thirdly, the suitability density values were normalized within the 0–1 range using the min–max normalization method to make their range uniform (Milligan and Cooper, 1988). Finally, the optimal number of clusters was identified by mean results of Silhouette (Kaufman and Rousseeuw, 2005), Calinski-Harabasz (Calinski and Harabasz, 1974), and Davies-Bouldin (Davies and Bouldin, 1979) indices. The selected indices summarize two cluster characteristics: the compactness of classes (i.e., how closely the suitability density values are grouped inside a cluster) and the partition between classes (i.e., how the clusters differ from each other).

The cluster analysis was then computed using a mixed hierarchical approach (Ward method) and partitioning methods (K-means algorithm, Tuffery, 2011). Firstly, hierarchical clustering analysis was performed based on Ward's minimum variance method (Ward, 1963). Then, the centroid of the hierarchical cluster is the starting point of the k-means partitioning method, in order to not compute it randomly (Tuffery, 2011). The combined use of these two methods improves the cluster analysis results, including the strengths of both methods, not a priori specification of the number of clusters in the Ward method, and the low computation efforts of the k-means algorithm (Tuffery, 2011).

Finally, the differences between clusters were assessed by the non-parametric Kruskal-Walls rank test, followed by the post-hoc Dunn's test with Holm-Bonferroni adjustment of p-values (Holm, 1979). Dunn's test was implemented using the function *dunn.test* included in the "dunn.test" R package (Dinno, 2017).

2.4.2. Non-metric multidimensional scaling ordination analysis

Three non-metric multidimensional scaling (NMDS) ordination analyses were performed (Fig. 1C). The first NMDS aimed to analyze the internal difference of suitability density values inside each cluster and within the three biogeographical regions. The second one aimed to quantify the current distribution pattern (i.e., number of invaded cells and aggregation vs. dispersion of the established population) of each invasive non-native plants in Italy. The last analysis aimed to separate groups of species, based on the suitability density and distribution patterns at the national level, thus classifying invasive non-native species into management types.

The first NMDS, using the same variables used in cluster analysis, ordered the invasive non-native plants, based on Euclidean distance and two dimensions, in the current and future scenarios in the three Italian biogeographical regions (Fig. 1C, Legendre and Legendre, 2012).

The second NMDS was computed to order the invasive non-native plants based on the current distribution pattern in Italy, within the European Environmental Agency grid (10 × 10 km), after removing GBIF multiple occurrences inside each cell in the Italian territory. Three spatial metrics were calculated (Fig. 1C, Table 1): 1) cell density (CD); 2) mean distance (MD) and 3) inverse of nearest neighbor index (INNI, Clark and Evans, 1954). Before performing the second NMDS, the values of the three spatial metrics (CD, MD, INNI) were prepared using the winsorization, and min–max normalization within the 0–1 range to standardize their range.

Table 1
Spatial metrics used for building the Non-metric Multidimensional scaling ordination analysis to estimate the cell density (CD), mean distance (MD) and inverse nearest neighbor index (INNI) of the invasive non-native plants in Italy.

Metric	Formula	Description	Range
CD	$\frac{n_i}{T}$	Cell Density: Number of invaded cells by i-invasive plant (n_i) divided by total number of cells in Italy (T). This index is a proxy for the abundance of the established populations at national level.	$0 \leq$ CD ≤ 1
MD	$\frac{\sum d_i}{n_i}$	Mean Distance: Sum of Euclidean distance between cells invaded by i-invasive plant (d_i) divided by number of cells invaded by i-invasive plant (n_i). This index is a proxy for the dispersion of the established population.	MD ≥ 0, no limit
INNI	$1/(\frac{\sum(\min(d_i)/n_i)}{0.5\sqrt{A/n_i}})$	Inverse Nearest Neighbor Index: Ratio between the sum of nearest neighbor distances observed and nearest neighbor distance in a hypothetical random distribution in Italy. D_i: Euclidean distance between cells invaded by i-invasive plant, n_i: number of cells invaded by i-invasive plant, A: extension of Italy in km^2. This index is a proxy of the aggregation of the established population.	INNI ≥ 0, no limit INNI < 1 – dispersion INNI ≥ 1 – clustering

The ensemble analysis of the three NMDS is necessary to achieve our objective to separate the species by their suitability density in the current and future scenarios, first at the biogeographical level, then to assess the distribution pattern at national level and finally to prioritize the types of management both at national level and at biogeographical level (Fig. 1C).

The NMDS ordination analyses were implemented using the function *metaMDS* included in the "vegan" R package (Oksanen et al., 2022).

2.4.3. Prioritization and classification of management

Three main types of management actions (Fig. 1C) for the invasive non-native species at a national scale or for a specific biogeographical region of Italy (i.e., Alpine, Continental and/or Mediterranean) were considered, according to the Convention on Biological Diversity (COP 6 Decision VI/23) and applied to this research as follows: "eradication" (invasive non-native species with high suitability density in both current and future climate with a low number of invaded cells, and possibly with a high aggregation of their occurrences in restricted areas and a low mean distance, meaning that they are in a few regrouped cells (i.e., low dispersion), and/or invasive non-native species with very low cell density, i.e., two single occurrences with a large distance between them); "control and containment" (i.e., invasive non-native species with a high suitability density in one or more biogeographical regions, with medium number of invaded cells (i.e., cell density) and with a medium mean distance (i.e., sparse occurrences in areas that could act as non-native sources for spread); and "monitoring" (i.e., invasive non-native species with high suitability density in both current and future climate at national scale, and possibly widespread in Italy so that eradication is no longer advisable). Additionally, two subcategories were assigned: (1) Monitoring into natural areas (MNA) = control the population when the naturalization process in natural areas begins to be evident, then wilderness management is recommended, to protect intact ecosystems and to pursue natural processes), (2) Monitoring into local and specific habitats (MLSH) = control the population locally and in certain habitat types, but where national eradication is no longer feasible. The excluded species due to the data deficient on their global distribution were also included in the management type as "monitoring" category since experts pointed out that these species are invasive in Italy.

To group the invasive non-native plants into management actions, information from the results of the third NMDS was used. To group species according to the three main suggested management types, we used the data from the sum of the current and future suitability density of each biogeographic region, the distribution pattern in Italy and the number of regions where plants are considered naturalized or invasive in Italy (https://dryades.units.it/floritaly/index.php).

Finally, two classes of priorities were proposed since they will help to prioritize management actions: "high" and "low" priority. Each species was evaluated based on the three management categories as follows (Fig. 1C).

3. Results

3.1. Invasive non-native plants identified by the national working group

Thanks to the knowledge of the SBI experts, it was possible to draw up a list of 36 invasive non-native plants to be considered for a proposal to the EPPO and further to be used for the prioritization process. These invasive non-native plants exert negative impacts on biodiversity (or potential impacts) and on ecosystem services. Most of them can also be considered as emergent invasive as they are in the start of the process of invasion in Italy. Furthermore, there are well known pathways of introduction and spread (for more details see Table S4, where the pathways of introduction are reported in accordance with the CBD guidance – Convention on Biological Diversity, 2018).

The list includes 36 invasive non-native plants with low to high probabilities of invading the three biogeographical regions of Italy for which the prioritization process was run. However, two of them were not considered for SDM, cluster analysis, NMDS and prioritization. In particular, *Agave fourcroydes* Lem. was excluded due to the low number of occurrences downloaded from GBIF after the cleaning process (no. <100). The second species, *Acacia pycnantha* Benth. was excluded in a second step since the bioclimatic suitability values inside the three Italian biogeographical regions were below the suitability threshold values (no. of suitability cells equal to 0). Overall, 34 of 36 species were used to apply the prioritization framework (Table S4). Importantly, we did not apply the prioritization process on two species (i.e. *Acacia pycnantha* and *Agave fourcroydes*) due to data deficiency on their global distribution which in one case was also a constraint to run MaxEnt. However, SBI experts pointed out that these two species are invasive in Italy (for the Mediterranean biogeographic region) and therefore we consider that it is important to collect more information to be available as soon as possible to fully apply the prioritization process. In this concern, they are included in the monitoring category as data deficient species.

3.2. Current and future bioclimatic suitability in the three Italian biogeographical regions

Overall, a total of 245 bioclimatic suitability models in the current and future scenarios were performed (Figs. S1–S12) and an average of 8 variables were used for the models (Table S3). A total of 34 invasive non-native plants achieved excellent predictive performances with mean values of AUC = 0.981 ± 0.023 and CBI = 0.968 ± 0.030 (Table S5). Generally, the suitability percentage values in current and future bioclimatic conditions were high for Mediterranean and Continental biogeographical regions.

In the current bioclimatic conditions, analyzing the suitability density separately in the three bioregions of Italy, 24 and 20 invasive non-native plants were classified as high and very high suitability density classes. Furthermore, 8 and 6 were classified as low and medium in the Mediterranean and Continental biogeographical regions, respectively.

Only two emerging invasive non-native plants (i.e., *Dactyloctenium aegyptium* (L.) Willd. and *Vachellia karroo* (Hayne) Banfi & Galasso) presented very low suitability density in the Mediterranean, while in the Continental region this class includes 8 emerging invasive non-native plants. Under current conditions a total of 20 invasive non-native plants were classified in the very low suitability density class in the Alpine biogeographical region (Fig. 2).

The overall suitability density in the future scenarios showed differences concerning the current climate values, although some values remained in the same class of high suitability density (e.g., 22 species in the Mediterranean and 12 species in the Continental), and in some cases, increasing the suitability density to high and very high (e.g., 11 species in the Mediterranean and two species in the Continental) for short and long term projections (Fig. 2).

In the Mediterranean biogeographical region, some species decreased their suitability density from very high to high class (*Cyperus eragrostis*), from high to medium (*Nelumbo nucifera*, *Parkinsonia aculeata*, *Robinia pseudoacacia*), from medium to low (*Acer negundo*, *Chasmanthe floribunda*), and from low to very low (*Sida rhombifolia*, Fig. 2).

In the Continental biogeographical region, climate change is causing variations in suitability density with an increase for seven invasive non-native plants (*Amaranthus emarginatus*, *Anredera cordifolia*, *Cenchrus longisetus*, *Dactyloctenium aegyptium*, *Mirabilis jalapa*, *Paraserianthes lophantha* subsp. *lophantha,* and *Parkinsonia aculeata*) and decrease for 12 invasive non-native plants (*Acer negundo*, *Agave americana*, *Arundo donax*, *Cyperus alternifolius*, *Cyperus eragrostis* subsp. *flabelliformis*, *Melia azedarach*, *Opuntia stricta*, *Pseudotsuga menziesii*, *Robina pseudoacacia*, *Salpichroa origanifolia*, *Senecio angulatus*, and *Yucca gloriosa*). In particular, *Cyperus eragrostis* and *Opuntia stricta* showed a very intense decrease in the suitability density class, changing from very high to low or very low classes considering all future climate scenarios (Fig. 2).

In the Alpine region, three species increased their suitability density to high or very high under future bioclimatic conditions (i.e., *Amaranthus emarginatus*, *Amaranthus retroflexus,* and *Artemisia annua*) and other three species (i.e., *Ambrosia psilostachya*, *Mirabilis jalapa,* and *Robinia pseudoacacia*) increase their suitability density reaching the medium class (i.e., 25–50 %, Fig. 1).

3.3. Prioritization of invasive non-native plants

3.3.1. Cluster analysis

The multi-collinearity analysis allowed us to select the six variables least correlated with each other (Table S6), in particular the current bioclimatic suitability density of the three Italian biogeographical regions (Current Alpine, Current Continental, Current Mediterranean) and other three variables in the short term scenarios: the SSP126 pathway for Alpine biogeographical regions (Future Alpine), the SSP370 pathway for Continental biogeographical regions (Future Continental), and the SSP585 pathway for Mediterranean biogeographical regions (Future Mediterranean). After, the results of Silhouette, Calinski-Harabasz, and Davies-Bouldin indices were homogenous identifying the optimum number of clusters as three (Fig. S2).

Cluster 1 comprised 12 invasive non-native plants (*Acer negundo*, *Agave americana*, *Amaranthus emarginatus*, *Amaranthus retroflexus*, *Ambrosia psilostachya*, *Artemisia annua*, *Bidens vulgata*, *Mirabilis jalapa*, *Nelumbo nucifera*, *Phyllostachys aurea*, *Robinia pseudoacacia,* and *Sorghum halepense*, Fig. 3a) showing a higher suitability density value in all three Italian biogeographical regions. Its peaks of suitability density values are reached in the Continental biogeographical region during the current climate (mean: 87.49 ± 9.75 %, Fig. 3c) and future climate (mean: 86.75 ± 11.40 %, Fig. 3f).

Cluster 2 included 12 invasive non-native plants (*Anredera cordifolia*, *Arundo donax*, *Cyperus alternifolius* subsp. *flabelliformis*, *Cyperus eragrostis*, *Cenchrus longisetus*, *Melia azedarach*, *Opuntia stricta*, *Paraserianthes lophantha* subsp. *lophantha*, *Salpichroa origanifolia*, *Senecio angulatus*, *Yucca gloriosa,* and *Zantedeschia aethiopica*, Fig. 3a) showing a

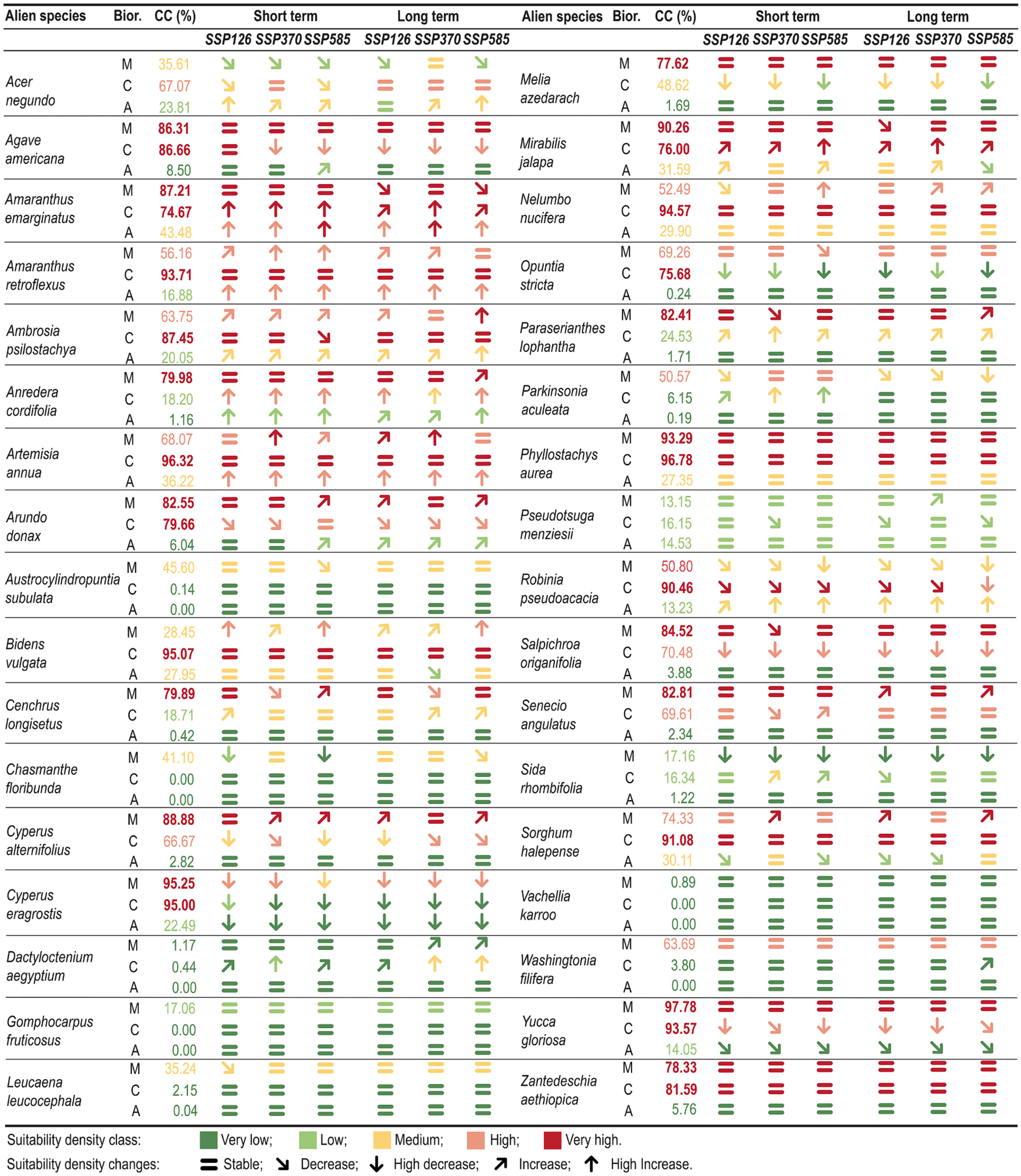

Fig. 2. Suitability density results, coming from the species distribution models (SDMs), for 34 invasive non-native plants in the three Italian biogeographical regions (i.e., Bior.: Biogeographical regions, A: Alpine; C: Continental and M: Mediterranean) based on the current climate (CC%: values shown in percentage, ranged from 0 to 100) and in the three future scenarios (SSPs) for two periods (Short Term and Long Term). Colored narrows show model predicted suitability density (%) in the future scenarios, where the colors are based on the suitability density classes: very low (0–10 %), low (10–25 %), medium (25–50 %), high (50–75 %) and very high (75–100 %) and the symbols represent the differences obtained when classified into: no change (±0 to 5 %), decrease (−5 to −15 %), high decrease (−15 to −100 %), increase (+5 to +15 %), high increase (+15 to +100 %).

higher suitability density values inside the Mediterranean biogeographical region for current and future climatic conditions (mean: 83.28 ± 7.77 % and 80.58 ± 13.63 %, respectively, Fig. 3b and e).

Cluster 3 contains 10 invasive non-native plants (*Austrocylindropuntia subulata*, *Chasmanthe floribunda*, *Dactyloctenium aegyptium*, *Asclepias fruticosa*, *Leucaena leucocephala* subsp. *glabrata*, *Parkinsonia aculeata*, *Pseudotsuga menziesii*, *Sida rhombifolia*, *Vachellia karroo,* and *Washingtonia filifera*, Fig. 3a) showing the lowest suitability density values in all Italian biogeographical regions in the current and future scenarios, with suitability density values always below 25 % (Fig. 3b–g).

3.3.2. Non-metric multidimensional scaling ordination analysis

The first NMDS ordination showed the relationships between the

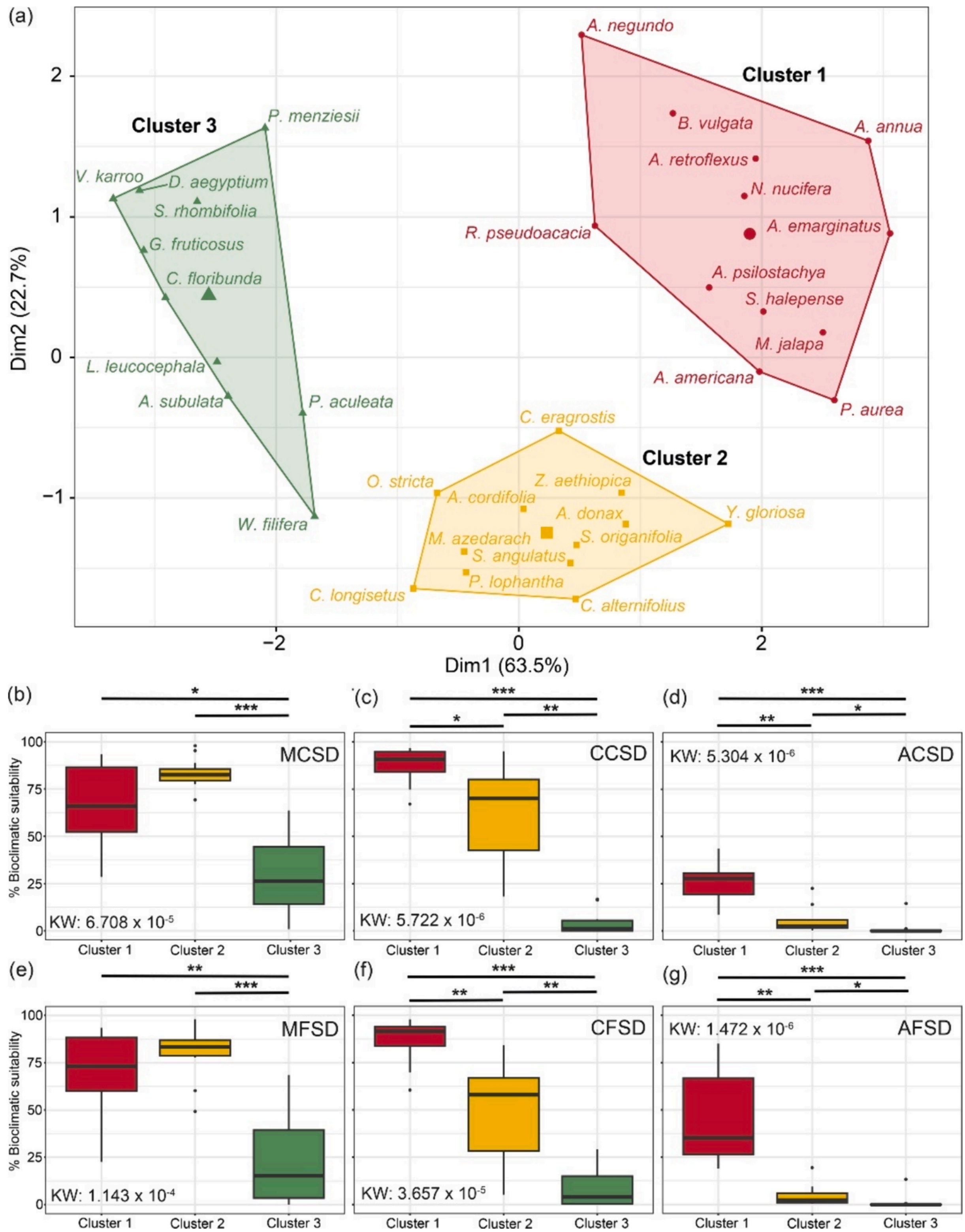

Fig. 3. The results of the cluster analysis show a) a two-dimensional graph with three clusters grouping the species according to the suitability density considering current and future conditions for each invasive non-native plant in three Italian biogeographical regions and six box plots showing the statistical difference between the three clusters as follows: b) MCSD (Mediterranean Current Suitability Density); c) CCSD (Continental Current Suitability Density); d) ACSD (Alpine Current Suitability Density); e) MFSD (Mediterranean Future Suitability Density); f) CFSD (Continental Future Suitability Density); g) AFSD (Alpine Future Suitability Density). P-value: *** < 0.001, ** < 0.01, * < 0.05.

suitability density values of the invasive non-native plants in the current and future bioclimatic conditions (i.e., the same variables selected after the multi-collinearity analysis) in the three Italian biogeographical regions, highlighting the well-defined differentiation between the clusters and their internal gradients (2D stress: 0.081, Non-metric fit R^2: 0.993, Linear fit R^2: 0.971, Fig. 4).

The invasive non-native plants grouped in cluster 1 (see Fig. 3 the red one), particularly related to the Continental biogeographical region, have an exception by *Agave americana*, which appeared to find more suitable conditions also in the Mediterranean biogeographical region, as well as *Acer negundo*, *Bidens vulgata*, and *Robinia pseudoacacia*, which appeared to find more suitable conditions also in the Alpine biogeographical region (Fig. 4).

The invasive non-native plants grouped in cluster 2 (see Fig. 3 the yellow one) find more suitable conditions in the Mediterranean. However, three of them (*Arundo donax*, *Yucca gloriosa,* and *Zantedeschia aethiopica*) were slightly more related also to the current climate in the Continental biogeographical region.

Finally, the invasive non-native plants grouped in cluster 3 (see Fig. 3 the green one) showed weaker relationships within the Italian biogeographical regions in both current and future bioclimatic conditions, except for *Washingtonia filifera* which showed intermediate suitable density values in the Mediterranean biogeographical region, while *Pseudotsuga menziesii* was related in the current and future climate to the Alpine biogeographical region (Fig. 4).

The second NMDS ordination (2D stress: 0.004, Non-metric fit R^2: 0.998, Linear fit R^2: 0.994) ordered the invasive non-native plants with their distribution pattern in Italy (Fig. 5).

Amaranthus retroflexus, *Acer negundo*, *Mirabilis jalapa*, *Robinia pseudocacia*, *Sorghum halepense* (i.e., grouped in cluster 1) and *Arundo donax* (i.e., included in cluster 2) showed a high and positive correlation with high values of cell density, meaning a very high invasion in Italy.

The presence of *Amaranthus emarginatus* (i.e., included in cluster 1) and *Chasmanthe floribunda*, *Washingtonia filifera* (i.e., grouped in cluster 3) is highly correlated with a significant distance between the presence of the species (i.e., closeness to the mean distance), meaning that they were poorly represented in Italy.

Furthermore, *Ambrosia psilostachya*, *Phyllostachys aurea* (i.e., grouped in cluster 1), *Melia azedarach* (i.e., grouped in cluster 2), and *Asclepias fruticosa*, *Leucaena leucocephala* subsp. *glabrata*, *Parkinsonia aculeata*, (i.e., grouped in cluster 3) were positively correlated with the Inverse Nearest Neighbor Index (INNI), indicating an aggregation of their occurrences in restricted areas (Fig. 5).

3.3.3. Priority classification

The third NMDS ordination (2D stress: 0.004, Non-metric fit R^2: 0.998, Linear fit R^2: 0.994) allowed us to order the invasive non-native plants within their suitability density in the current and future scenarios and their distribution pattern in Italy (Fig. S14). This last NMDS was used to classify the selected 34 invasive non-native plants into three main types of management actions and designate each as a priority based on the management type following the scheme proposed for the classification (Fig. 2).

Amaranthus emarginatus, *Bidens vulgata*, *Leucaena leucocephala* subsp. *glabrata*, *Nelumbo nucifera, Paraserianthes lophantha* subsp. *lophantha*, *Phyllostachys aurea,* and *Sida rhombifolia* were classified in the group “eradication”, i.e., species showing a high and positive correlation with high values of suitability density in the current and future scenarios, low cell density and mean distance and with a high aggregation of their occurrences in restricted areas. These species are expected to represent a threat in the early stages of invasion at national scale (i.e., *Amaranthus emarginatus*) or inside two biogeographical regions (i.e., *Paraserianthes lophantha* subsp. *lophantha* for Mediterranean and Continental bioregion) or a specific biogeographical region (i.e., *Leucaena leucocephala* for Mediterranean bioregion) and actions such as eradication are needed to tackle them.

Amaranthus retroflexus, *Arundo donax*, *Robinia pseudoacacia*, and *Sorghum halepense* were species with a high suitability density in both current and future scenarios at national scale or at least in one biogeographical region and are widespread in Italy. In addition, *A. retroflexus* and *S. halepense* are considered serious agricultural weeds, then “monitoring” is proposed. *Pseudotsuga menziesii* and *Washingtonia filifera*

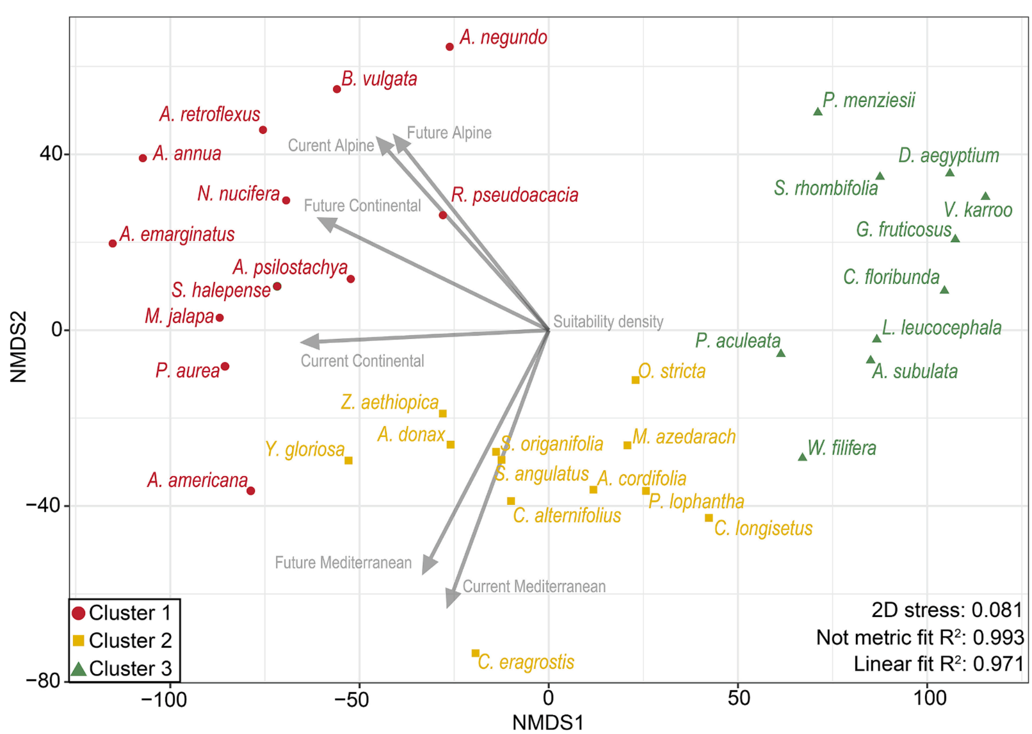

Fig. 4. Nonmetric multidimensional scaling (NMDS) plot shows a Euclidean distance and two dimensions dissimilarity of invasive non-native plants based on the current and future scenarios in the three Italian biogeographical regions.

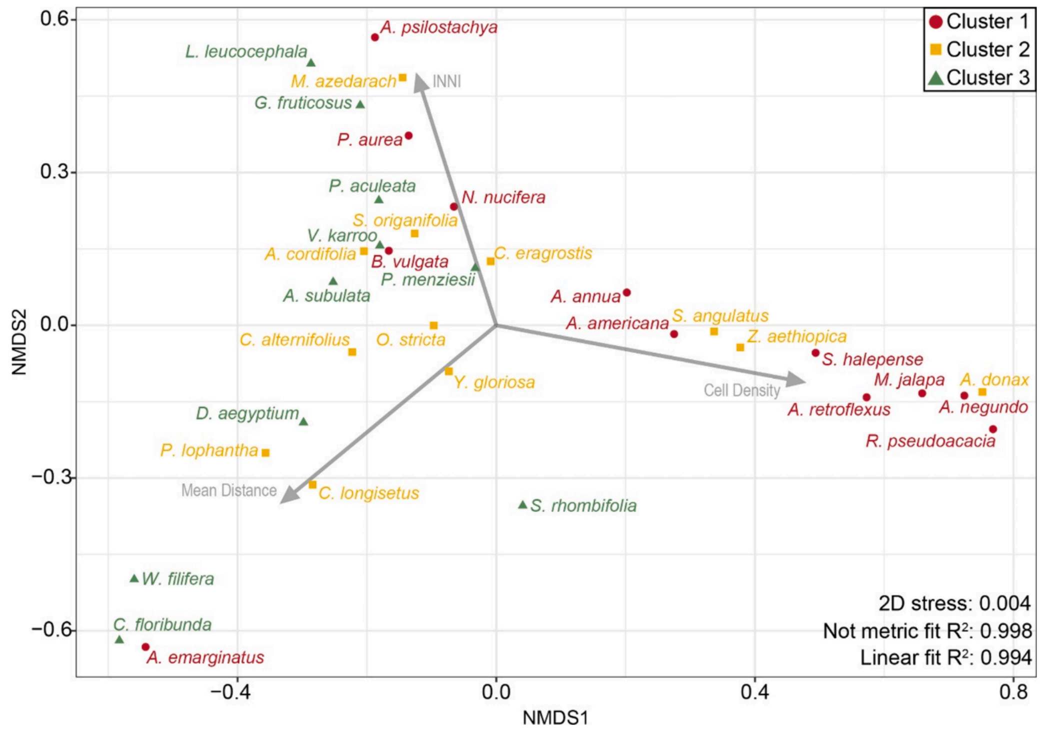

Fig. 5. Nonmetric multidimensional scaling (NMDS) plot shows a Euclidean distance and two dimensions of invasive non-native plants based on the current spatial metrics to estimate the cell density, the mean distance and inverse of nearest neighbor index of the invasive non-native plants in Italy.

were also classified for monitoring. These species are quite commonly planted in many Italian regions but are not widespread in Italy as naturalized in the natural environment, consequently wilderness monitoring is recommended to protect natural ecosystems. Additionally, *Acacia pycnantha* and *Agave fourcroydes* (i.e., data deficient species) were included in "monitoring" category. The other 21 invasive non-native plants were classified as "control and containment" at the national level or in a specific biogeographical region (see Table 2).

4. Discussion

Within the proposed framework, we applied a reproducible prioritization procedure based on open access data (i.e., GBIF occurrences), supported by an integration of SDMs (using current and future scenarios on climate change to disentangle biogeographical regions where the plant invaders could potentially establish and spread), cluster analysis, and analysis of distribution patterns on invasive non-native species with the support of expert knowledge.

The framework considers the climatic suitability density in the biogeographical regions of Italy, and the current status of invasion of each invasive non-native species in the administrative regions of Italy and it suggests two priority classes (high and low) for management actions such as eradication, control and containment, and monitoring. However, the proposed framework does not consider the impacts and the feasibility of the strategy of management, as both these two elements may be taken into account in a second step and may vary according to the political and socioeconomic context, or little information might be available in the first stage. As discussed below, at a country level, the national strategy for prioritization must take in account a number of additional criteria, such as, e.g., the full list of regulated species, including international commitments to control specific species or pathways, and national capacities to prevent and manage plant invasions (Early et al., 2016).

Despite the availability of many prioritization methods (Brunel et al., 2010; Booy et al., 2017; Bertolino et al., 2020), for example to prioritize species, pathways, sites (McGeoch et al., 2016) and management actions according to impacts (Convention on Biological Diversity, 2022b; Booy et al., 2017; Kumschick et al., 2012; Renteria et al., 2017), quite often information on impacts is scarce and integration of different methods and criteria in different steps, or when information become available, may be very useful (e.g., N'Guyen et al., 2016). For example, a single large population may require more effort than a few small populations of the same species, and this could influence the success of eradication or control since the resources allocated to control the species will be different depending on the density of invaded area (Wilson et al., 2013). Additionally, an economic estimate could support prioritization decisions evaluating the work effort required in terms of number of workers, tools used, and time taken to eradicate each species. The effectiveness of eradication efforts also depends on species traits, for example herbaceous species, usually, require less effort than thorny and/or toxic trees, the capacity to accumulate a persistent seed bank or belowground organs hinders control, and such plant trait data may not be available for many non-native species and may vary in the new ranges (Renteria et al., 2017) or along the naturalization-invasion continuum.

Global standard methods like IUCN/EICAT are available for estimating and categorizing the potential environmental impacts of invasive alien species, including plants (Kumschick et al., 2024). However, they require significant amounts of information which may not be always available for many invasive non-native species. For these reasons, our framework could represent a convenient screening method for large numbers of species, with limited available information for most of them, and can be considered as a first step of a longer ongoing process, whenever additional information become available.

Our modeling approach is based on a single algorithm and on presence-only data. Just as information on impacts may be missing or insufficient, also good quality distribution data may be limited. However, this part of the framework can be run again whenever new information on the distribution, or better climatic scenarios, may become available. In fact, some species for which we did not have sufficient occurrence records could not be included in subsequent analyses and were excluded from prioritization. Nonetheless, local and expert knowledge can be used to refine potential lists further (Jarnevich et al.,

Table 2
List of the 34 invasive non-native plants classified in three management categories (eradication, control and containment and monitoring) within two management type priorities (high or low) at a national scale or in a specific Italian biogeographical region. Alp = Alpine, Con = Continental, Med = Mediterranean. Monitoring into natural areas (MNA) = control the population when the naturalization process in natural areas begins to be evident, then wilderness management is recommended, to protect intact ecosystems and to pursue natural processes) and Monitoring into local and specific habitats (MLSH) = control the population locally and in certain habitat types, but where national eradication is no longer feasible.

Non-native plants	Management type	Management scale	Management type priority
Nelumbo nucifera Gaertn.	Eradication	National	High
Amaranthus emarginatus Salzm. Ex Uline & W.L. Bray	Eradication	National	Low
Bidens vulgata Greene	Eradication	National	Low
Phyllostachys aurea Carrière ex Rivière & C.Rivière	Eradication	National	Low
Paraserianthes lophantha (Willd.) I.C.Nielsen subsp. *lophantha*	Eradication	Med and Con	High
Leucaena leucocephala (Lam.) de Wit subsp. *glabrata* (Rose) Zárate	Eradication	Med	High
Sida rhombifolia L.	Eradication	Med	Low
Ambrosia psilostachya DC.	Control and containment	National	High
Mirabilis jalapa L.	Control and containment	National	High
Acer negundo L.	Control and containment	National	Low
Agave americana L.	Control and containment	National	Low
Artemisia annua L.	Control and containment	National	Low
Anredera cordifolia (Ten.) Steenis	Control and containment	Med and Con	High
Cenchrus longisetus M.C. Johnst.	Control and containment	Med and Con	High
Cyperus alternifolius L. subsp. *flabelliformis* Kük.	Control and containment	Med and Con	High
Melia azedarach L.	Control and containment	Med and Con	High
Salpichroa origanifolia (Lam.) Baill.	Control and containment	Med and Con	High
Senecio angulatus L.f	Control and containment	Med and Con	High
Yucca gloriosa L.	Control and containment	Med and Con	High
Zantedeschia aethiopica (L.) Spreng.	Control and containment	Med and Con	High
Cyperus eragrostis Lam.	Control and containment	Med and Con	Low
Opuntia stricta (Haw.) Haw.	Control and containment	Med and Con	Low
Parkinsonia aculeata L.	Control and containment	Med	High
Austrocylindropuntia subulata (Muehlenpf.) Backeb.	Control and containment	Med	Low
Chasmanthe floribunda (Salisb.) N.E.Br.	Control and containment	Med	Low
Dactyloctenium aegyptium (L.) Willd.	Control and containment	Med	Low
Asclepias fruticosa L.	Control and containment	Med	Low
Vachellia karroo (Hayne) Banfi & Galasso	Control and containment	Med	Low
Amaranthus retroflexus L.	Monitoring	National	High
Robinia pseudoacacia L.	Monitoring (MLSH)	National	Low
Sorghum halepense (L.) Pers.	Monitoring	National	Low
Arundo donax L.	Monitoring (MLSH)	Med and Con	High
Pseudotsuga menziesii (Mirb.) Franco	Monitoring (MNA)	Alp and Con	High
Washingtonia filifera (Linden ex André) H. Wendl. ex de Bary	Monitoring (MNA)	Med	Low

2023). Importantly, our study confirms the observed trend of expansion of the species' distribution area due to climate change. This trend can be accelerated by future socioeconomic scenarios (He et al., 2023). What emerged from our results is that the expansion of the range of invasive non-native species in Italy under different future climate scenarios requires careful consideration when planning and implementing conservation measures.

In the proposed framework the "eradication" management action was suggested for species of high invasion risk, since they have high suitability density in current and future scenarios, which are in an early stage of invasion, with populations restricted to few locations or in a specific Italian biogeographical region. This is the case of one hydrophyte (*Nelumbo nucifera*), two phanerophytes (*Paraserianthes lophantha* subsp. *lophantha*, and *Leucaena leucocephala* subsp. *glabrata*), and a chamaephyte (*Sida rhombifolia*). *Leucaena leucocephala* subsp. *glabrata* is a global well-known invader in natural habitats (Wolfe and Van Bloem, 2012), and in Europe, particularly on islands, it is invading pseudo-steppe with grasses and annuals of the *Thero-Brachypodietea* plant communities (habitat 6220* Directive 92/43/CEE, Minissale et al., 2023). *Sida rhombifolia* constitutes a serious nuisance for agricultural lands, pastures, and native grasslands (Reddy, 2011). This species inhabits thermophilous grass anthropogenic vegetation rich in nitrophilous therophytes with a summer-autumn cycle (Cambria et al., 2022).

On the other hand, when eradication is no longer advisable, "control and containment" was proposed at the national level, or in a specific Italian biogeographical region, to limit the spread to a defined area. This is the case of *Ambrosia psilostachya* which has a dominant stand in Italian coastal dunes (Montagnani et al., 2017), *Mirabilis jalapa*, a common ornamental escaped from cultivation, thriving in ruderal areas and along roads, and *Salpichroa origanifolia*, a ruderal species escaped long ago from botanical gardens which has recently invaded forest ecosystems (Arduini and Alessandrini, 2024). Finally, we proposed "monitoring" for those species already widespread at the national level, such as *Robinia pseudoacacia* (neophyte) and *Arundo donax* (archaeophyte), aiming to prevent their further spread or for those species widely planted such as *Pseudotsuga menziesii* and *Washingtonia filifera* to be prepared to start the control as soon as naturalization process (wildening) would start in natural areas. *Robinia pseudoacacia,* an invasive tree in Europe (Vítková et al., 2017), is included in the regional blacklists of invasive species (i.e., Management List) of the Piedmont region and in the Lombardy region (Italy) for monitoring and control. Nevertheless, management measures prescribed by regional blacklists do not prohibit the cultivation of this species, except for some environmental contexts (e.g., natural areas) since *Robinia pseudoacacia* may provide profits or benefits in agroforestry systems (Sádlo et al., 2017). However, its management should be maintained under the scope of national legislation (Crosti et al., 2016). Therefore, it is logical that these species are prioritized, and immediate actions are taken by organizing surveillance programs (Kenis et al., 2022).

The results of the proposed framework must take into account the regulation in force on non-native plants, as the management of the 36 species prioritized in the present study should be harmonized with the existent national obligation. To date the system of the EPPO lists (EPPO, 2024) includes a total of 126 plant species, respectively four species in the A1 List, 31 in the A2 List (A1/A2 stand for pests recommended for regulation as quarantine pests), 50 in the List of Invasive Alien Plants (IAP), 26 in the Observation List of IAP and 15 in the Alert List. Of the above-mentioned listed species, a total of 86 are also present in Italy, more specifically 19 in the A2 List, 41 in the List of IAP, 16 in the Observation List and 10 in the Alert List (Table S7 Supplementary material). Those species are present in different status, from casual to invasive, and 18 species are both EPPO A1/A2 and invasive alien species of Union concern according to the Regulation (EU) n. 1143/2014, as in the case of *Pontederia crassipes*, and *Acacia saligna*. The management of the EPPO list species follows the Italian regulation on plant health (National Decree 19 August 2005, no. 214, *ex* Directive 2002/89/CE) while the management of the species of Union concern follows the National Decree 15 December 2017, no. 230. Furthermore, a number of other non-native species or genera are regulated at the level of single Italian administrative regions (Brundu et al., 2020; Table S7), so that all these aspects should be taken into account in a national strategy.

5. Conclusion

We designed and tested a replicable framework to prioritize management actions based on climatic suitability density and on distribution patterns in the three biogeographical regions of Italy, under various climatic scenarios. Such methodology could be further implemented in other territories, and with additional criteria. We are convinced that our results and the proposed framework match the demand for replicable new early warning tools, i.e., for predicting the location of new outbreaks, for establishing priorities for eradication, control and containment and monitoring of invasive non-native species.

We provide a list of 36 invasive non-native species in order of priority as to which species should be considered for different types of management and propose them to the EPPO through the NPPO to be evaluated further using innovative tools (see Vilizzi et al., 2024).

CRediT authorship contribution statement

Vanessa Lozano: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Flavio Marzialetti:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Alicia Teresa Rosario Acosta:** Writing – review & editing, Data curation. **Iduna Arduini:** Writing – review & editing, Data curation. **Gianluigi Bacchetta:** Writing – review & editing, Data curation. **Gianniantonio Domina:** Writing – review & editing, Data curation. **Valentina Lucia Astrid Laface:** Writing – review & editing, Data curation. **Valerio Lazzeri:** Writing – review & editing, Data curation. **Chiara Montagnani:** Writing – review & editing, Data curation. **Carmelo Maria Musarella:** Writing – review & editing, Data curation. **Gianluca Nicolella:** Writing – review & editing, Data curation. **Lina Podda:** Writing – review & editing, Data curation. **Giovanni Spampinato:** Writing – review & editing, Data curation. **Gianmarco Tavilla:** Writing – review & editing, Data curation. **Giuseppe Brundu:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112279.

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