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Using structured eradication feasibility assessment to prioritise the management of new and emerging invasive alien species in Europe

Running title: prioritising IAS management in Europe

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Abstract

Prioritising the management of invasive alien species (IAS) is of global importance and within Europe integral to the EU IAS regulation. To prioritise management effectively the risks posed by IAS need to be assessed, but so too does the feasibility of their management. While the risk of IAS to the EU has been assessed, the feasibility of management has not.

We assessed the feasibility of eradicating 60 new (not yet established) and 35 emerging (established with limited distribution) species that pose a threat to the EU, as identified by horizon scanning. The assessment was carried out by 34 experts in invasion management from across Europe, applying the Non-Native Risk Management scheme to defined invasion scenarios and eradication strategies for each species, assessing the feasibility of eradication using seven key risk management criteria. Management priorities were identified by combining scores for risk (derived from horizon scanning) and feasibility of eradication.

The results show eradication feasibility score and risk score were not correlated, indicating that risk management criteria evaluate different information than risk assessment. Seventeen new species were identified as particularly high priorities for eradication should they establish in the future, while fourteen emerging species were identified as priorities for eradication now. A number of species considered highest priority for eradication were terrestrial vertebrates, a group that has been the focus of a number of eradication attempts in Europe. However, eradication priorities also included a diverse range of other taxa (plants, invertebrates and fish) suggesting there is scope to broaden the taxonomic range of attempted eradication in Europe. We demonstrate that broad scale structured assessments of management feasibility can help prioritise IAS for management. Such frameworks are needed to support evidence based decision making.

Introduction

Managing the increasing risks and impacts of invasive alien species (IAS, cf. invasive non-native, invasive non-indigenous species) is one of the great societal challenges of the 21st century (Seebens *et al.*, 2018, Simberloff *et al.*, 2013, Vilà *et al.*, 2011). Ambitious international goals aim to reduce or halt these rising impacts, including Aichi Target 9 of the Convention on Biological Diversity (CBD, 2014), which commits signatories to control or eradicate priority species. This commitment is reflected in European Union (EU) regulation 1143/2014 on IAS (EU, 2014). However, the control or eradication of IAS can be expensive. With numerous species and limited resources, decision makers must carefully prioritise which species to manage and how (McGeoch *et al.*, 2016).

Risk assessment, the process by which the likelihood and magnitude of impact is assessed, is commonly used to support the prioritisation of IAS and has been well used in Europe and elsewhere (Roy *et al.*, 2018). However, simply assessing the risks and impacts of IAS is of limited use for prioritising their management, as it fails to take into account the feasibility of delivering an effective response (Booy *et al.*, 2017). Failure to account for management feasibility can result in species being prioritised that may be unmanageable or for which management is unlikely to be economically viable (Branquart *et al.*, 2016, Cassey *et al.*, 2018, Courtois *et al.*, 2018). As a result resources could be wasted or used inefficiently and confidence in decision making could be reduced.

A number of approaches are available to support the assessment of IAS management feasibility, its costs and benefits. Economic cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) have been used to assess aspects of management for particular species and in some cases to approve management plans prior to implementation (Blackwood *et al.*, 2010, Born *et al.*, 2005, Courtois *et al.*, 2018). However, purely economic CBA and CEA approaches generally require large quantities of empirical information, are costly and time-consuming to produce (Reyns *et al.*, 2018). There are also complexities in how to effectively monetise the full range of social, environmental, animal welfare and biodiversity consequences of IAS management (Hoagland & Jin, 2006). As a result, CBA and CEA are generally applied to individual IAS and particular situations (Panzacchi *et al.*, 2007, Rajmis *et al.*, 2016), but are difficult to apply across large numbers of different species to identify broad management priorities.

Multi-criteria approaches (Born *et al.*, 2005), including Multi Criteria Decision Analysis (MCDA), provide a means of assessing and comparing between larger numbers of species using available data against a wide range of different criteria, without the need for monetisation. As such, they are commonly used to support risk assessment, as well as risk management evaluations in some cases (EPPO, 2011, OiE, 2017, Mehta *et al.*, 2010). One such approach is the Non-Native Risk Management (NNRM) scheme (Booy *et al.*, 2017), which uses multiple criteria relevant to decision makers (beyond solely monetary considerations) to score different aspects of IAS management, based on pre-defined invasion scenarios and strategies. Within this scheme, species are assessed using expert judgement and elicitation methods, incorporating empirical information where available and including a framework for assessing confidence (Roy *et al* 2020). This approach is similar to methods used for IAS risk assessment (Baker *et al.*, 2008, Brunel *et al.*, 2010, Copp *et al.*, 2016, Essl *et al.*, 2011, Mumford *et al.*, 2010, Vanderhoeven *et al.*, 2017) and increasingly throughout the field of ecological conservation (Adem Esmail & Geneletti, 2018, Burgman *et al.*, 2011).

To date, the NNRM has been applied at regional (Osunkoya *et al.*, 2019) and national scales (Adriaens *et al.*, 2019, Booy *et al.*, 2017); however, there are advantages of applying it at larger scales. IAS pose threats to multiple countries and do not respect national boundaries, meaning that management responses will often require cooperation and resource sharing between states to be effective (Robertson et al 2015). Large-scale prioritisation is currently of particular relevance in the EU to support the implementation of the Regulation 1143/2014 on the prevention and management of the introduction and spread of IAS.

Here we apply the NNRM at a large scale to evaluate an existing multi-taxa list of new and emerging IAS that threaten the EU as identified by horizon scanning (Roy *et al.*, 2015, Roy *et al.*, 2019). We use this evaluation of species along with existing risk assessment scores (derived from horizon scanning) to consider potential priorities for management within Europe. In particular, we consider priorities for (i) early detection and rapid eradication of new species should they start to establish in Europe; and, (ii) eradication of species that are currently established in Europe, but with limited distributions. In addition, we provide an insight into potential priorities for (iii) prevention and (iv) long-term management. We explore the suitability of using this approach for large scale prioritisation and consider patterns in the feasibility of eradication in different environments and at different scales.

Materials and methods

A list of 95 species were identified as high or very high risk through the horizon scanning of Roy *et al.* (2015). This comprised terrestrial, freshwater and marine taxa that were categorised as either new to the EU (i.e. not yet established) or emerging (i.e. established with limited distributions) (Table 5.1). For each species, a risk management assessment was completed using a modified version of the Non-Native Risk Management (NNRM) scheme (Booy *et al.*, 2017). A key modification was to standardise invasion scenarios using pre-defined categories for the number of discrete populations (1-3, 4-10, 10-50, +50) and total combined area of all populations (<1ha, 1-10ha, 10ha-1km2, 1-10km2, 10-100km2, >100km2; for more guidance refer to Methods S1). This helped take into account the greater complexity of assessment at the European scale and also allowed for patterns in feasibility of eradication at increasing area and number of populations to be analysed. Species were included that had a range of areas and populations (Table 5.2). However, as the focus of horizon scanning was on new and emerging species, most were at the low end of the scale (i.e. 1-3 populations covering less than 1ha in total). The full, modified scheme and guidance is available (Methods S1).

A combination of expert elicitation, review and consensus building methods were used to produce and validate risk management assessments following similar approaches to Roy *et al.* (2014), Booy *et al.* (2017) and the guiding principles of Roy *et al* (2020). In total, 34 experts were engaged in the elicitation process grouped into five taxonomic specialisms: freshwater animals, terrestrial vertebrates, terrestrial invertebrates, marine species and plants (excluding marine plants). Each group comprised 5-8 experts chosen by the organisers in cooperation with an appointed group leader based on proven experience of IAS management and representation of a range of European countries.

Risk management assessments were first drafted by expert groups using the NNRM template. The invasion scenario (a factual description of the current or potential distribution and spread of the species in Europe) and eradication strategy (a realistic combination of methods and techniques for eradication) for each species was completed by the group leader, in consultation with other experts in their group as necessary. For emerging species the scenario was the current distribution of the species in the risk management area. For new species, the most likely invasion scenario was used, based on the likely extent of the species at the point of detection in the wild in Europe given current surveillance. Each species was then assessed independently by at least three different experts from each group, who provided response and confidence scores for seven risk management components (effectiveness, practicality, cost, impact, acceptability, window of opportunity and likelihood of reinvasion) as well as scoring the overall feasibility of eradication. Assessment was based on expert judgement, taking into account available evidence and past management experience, with ratings justified by written comments and uncertainty recorded. All scores were collated, anonymised and returned to the expert group, along with the median response and confidence scores for each risk management component and the overall feasibility of eradication.

A two-day workshop (17-18 May 2016) was held to review, refine and ultimately agree on scores by consensus. Twenty-eight of the original experts, including all group leaders, attended. The first session was for group leaders only and aimed to reduce linguistic uncertainty with regards to feasibility criteria and scoring ranges, as well as clarifying the requirements of the rest of the workshop. To aid in this, each group leader presented the initial scores of their group, discussed any areas of potential ambiguity and agreed on clarifications. This was then repeated in plenary so that participants could go through the scoring guidance with the organisers and ensure consistency in application. The main workshop proceeded with a simplified, facilitated Delphi approach (Mukherjee *et al.*, 2015) including two rounds of consensus within and across expert groups:

1. Group leaders presented an overview of the initial scores from their groups to all participants, who were encouraged to discuss and challenge the scores.

2. Expert groups reviewed and refined the scores of their group, taking into account the discussions from session 1. Each group was provided with the median response and confidence scores for each of their species and asked to discuss disagreement on scores and refine them where necessary.

3. The final stage of the scoring process was to build consensus of all participants on the refined scores across all groups. Scores were collated and presented back in plenary by two facilitators (OB and PG), focussing on reaching consensus on the final overall feasibility of eradication score for each species. Participants were encouraged to discuss and challenge the scores of other groups with any changes at this point made with the consensus of the whole group.

Analysis

All analysis was undertaken in R (R Core Team 2020).

Risk Management Scores

We assessed the interrelation between the seven risk management components scores and the overall feasibility of eradication score in ordinal space using a factor plot and non-metric multi-dimensional scaling. A distance matrix of species by component was analysed using the *isoMDS* function in the MASS (Venables & Ripley, 2002) package and then visualised using FactoMineR package (Le *et al.*, 2008), colouring each species by the independent overall score. Underlying patterns of correlation between components (variables) were visualised in a factor plot.

Polychoric correlations (R package 'Polychor' (Fox, 2019)) were used to compare the ordinal scores for overall risk (derived from horizon scanning) and the overall feasibility of eradication scores (derived from this exercise). Correlation between the two assessments implies they measure similar underlying information; we did not expect to find strong correlation.

Note that these analyses were used to investigate the relationship between the assessed variables, but are not a requirement for those applying the risk management scheme in the future.

Effect of extent and environment on overall feasibility

To assess the relationship between the score for overall feasibility of eradication (ordinal response) and environment (terrestrial, freshwater, marine), total area and number of populations, a cumulative link model (CLM) was fitted using the R package 'Ordinal' (Christensen, 2018). It was hypothesised that the overall feasibility of eradication score for each species would decline with increasing spatial extent (total area and number of populations) and be dependent on the environment in which the species occurred. Population categories 'C' and 'D' were pooled into one category (10+ populations) as were areas >10Ha (greater than category 3) owing to sparse data at these ranges. Ordinal regression assumes proportional odds (i.e. the relationship between each pair of outcome groups is the same). Statistical tests for proportional odds have been criticised as they tend to falsely reject the null hypothesis, so proportionality was assessed using a graphical method following Bender and Grouven (1997) and Gould (2000). This method uses plots of predicted values derived from a series of binary logistic regressions to check the assumption that coefficients are equally separated across cut-points.

The final model was used to predict the feasibility of eradication for every combination of environment, total area and number of populations. Model predictions were expressed as the probability of the overall feasibility of eradication score being each of the five response levels (very high to very low) and visualised using the R package 'Ggplot2' (Wickham, 2009).

Prioritisation

To indicate priorities for eradication, we combined the overall risk assessment scores (derived from horizon scanning) with the overall feasibility of eradication scores (from this risk management exercise) in a prioritisation matrix (following Booy *et al.*, 2017). As both the overall risk and overall feasibility of eradication scores used a five-point scale (very low to very high) the result was a 5x5 prioritisation matrix, with priorities ranging from lowest (1:1) to highest (5:5) (Table 3). However, as only species with risk assessment scores of high and very high were included in this exercise, only positions in the top two rows of the matrix could be achieved, resulting in priorities ranging from medium-low (4:1) to highest (5:5).

The matrix was also used to investigate other priorities, including prevention and long-term management. For new species, prevention was likely to be a particular priority if the species posed a high risk and the feasibility of eradication after arrival was low. For emerging species, long-term management (e.g. containment, slowing spread, control) was likely to be a particular priority if the species posed a high risk and the feasibility of eradication was low. These priorities corresponded to the top left corner of the matrix and are marked: ++ highest, and + high priority for prevention / long-term management (Table 3).

Data

The data underpinning the analysis reported in this paper are deposited in the Dryad Data Repository (Booy *et al.*, 2020).

Results

Risk Management scores

The workshop resulted in consensus risk management scores for all species.

Scores for overall risk (derived from horizon scanning) and overall feasibility of eradication (derived from this exercise) were not correlated: polychoric correlation, rho = -0.281 +/- s.e. 0.136, Chi sq =0.519, p=0.89 (note rho is the test statistic where values near 0 indicate little agreement).

The scores for overall feasibility of eradication aligned in sequence with the individual component scores (i.e. effectiveness, practicality, cost, impact, acceptability, window of opportunity and likelihood of reinvasion) with some overlap (Figure S1). This suggests that while component scores were in general agreement with the overall score it was not possible to consistently determine the overall score based on individual components. Five of the risk management components (effectiveness, practicality, cost, impact and acceptability) were correlated with overall feasibility of eradication, while window of opportunity and likelihood of reinvasion were not (Figure S2).

Effect of extent and environment on the overall feasibility of eradication

The assumptions of proportionality were met for the cumulative link model as the thresholds (intercepts) for each covariate were broadly similar distances apart (Figure S3). All variables (environment, total area and number of populations) were significant predictors of the scores for overall feasibility of eradication (Figure S4).

In general, the scores for overall feasibility of eradication were lowest for marine species and highest for terrestrial species, with freshwater species in between. In each environment, overall feasibility of eradication decreased as total area occupied or number of populations of the IAS increased (Figure S4).

Increasing total area and number of populations reduced the probability of very high and high scores for overall feasibility of eradication in all environments (Figure 1). For terrestrial species, high overall scores for feasibility of eradication were more probable than low scores at every combination of total area and number of population. In the freshwater environment, high scores were probable when either the total area was small (<1ha) or there were few populations (<1-3), but beyond this low scores were more probable. For marine species, low scores were more probable than high scores at all combinations.

Prioritisation

Combining scores for overall risk (derived from horizon scanning) and overall feasibility of eradication resulted in six levels of eradication priority: highest (1 species), very high (20), high (36), med-high (20), medium (14) and med-low (4) (Figure 2). These were further divided into priorities for future rapid eradication of new species should they establish (Figure 2a) and eradication priorities for emerging species that are already established (Figure 2b). In addition, new (i.e. not yet established) species for which overall feasibility of eradication on detection was low were considered priorities for prevention (Table S1); while, emerging (i.e. already established) species with low feasibility of eradication were considered priorities for long-term management (e.g. control, slowing spread, containment) (Table S2). Detail on key eradication priorities is provided below and in Tables 4 and 5 (scores for all species are available in Tables S1 and S2).

Priorities for future rapid eradication of new species

Of the 60 new species, *Faxonius rusticus* (rusty crayfish) scored the highest priority for eradication, with both the overall risk and overall feasibility of eradication scoring very high (Table 4, Figure 2a). Note that at the time of assessment *F. rusticus* was not considered to be established in Europe, hence its inclusion here as a new species; however, the first European population was detected in France in 2019.

A further 16 species not yet established in the EU were assessed as very high priority for eradication, based on the most likely scenario at the point of detection: seven freshwater fish, three terrestrial plants, three insects, two mammals and one reptile (Table 4, Figure 2a). The invasion scenarios for these species suggested that the majority were likely to be in 1-3 populations covering <1 ha or 1-10 ha at the point of detection. However, two species were considered likely to be in more than 1-3 populations (Asian needle ant, *Pachycondyla chinensis*; and Nile tilapia, *Oreochromis niloticus*) and three were likely to cover 1-10 km^2 (American bison, *Bison bison*; brushtail possum, *Trichosurus vulpecula*; and *L. getula*). The bioregions that these species could invade included the Mediterranean (13), Macaronesia (12), Atlantic (8), Continental (7) and Steppic (6) bioregion.

Approximately twelve different methods of eradication were identified for these 16 species, including: shooting, trapping, manual destruction, mechanical removal, herbicide, electrofishing, fyke netting, piscicide, draining, angling, poison baiting and insecticide. The total estimated cost of eradicating all 16 species was in the region of €0.5-2.6M (based on the sum of lower and upper bounds for the risk management component cost). No significant (at the scale of Europe) adverse non-target impacts of management were considered likely. All eradications of these new species had high or very high acceptability, except for *Gambusia affinis* (western mosquitofish) which scored moderate because of potential negative reaction to the use of piscicides. The window of opportunity for most species was short (2 months - 1 year) with two species < 2 months, six species 1-3 years and one species (*B. bison*) 4-10 years.

Priorities for eradication of currently established emerging species

Of the 35 emerging species assessed, four were identified as very high priority for eradication and a further ten were identified as high priority (Table 5, Figure 2b).

The top four priority species were terrestrial vertebrates with very high scores for overall risk and high scores for overall feasibility of eradication. The invasion scenario for these species (based on current understanding of the situation in Europe at the time of assessment) suggested that they were established in no more than 3 populations, covering a minimum area of 1ha and maximum area of 100km^2 each. However, there was uncertainty about the status and extent of three of the four species (common myna, *Acridotheres tristis*, Berber toad, *Bufo mauritanicus* and red-vented bulbul, *Pycnonotus cafer*). Current populations of all four species were thought to be limited to Spain, except one population of *A. tristis* in Portugal. The estimated cost of eradicating each species ranged from very low (€1-50k) (*B. mauritanicus*) to moderate (€0.2-1M) (*A. tristis* and coati, *Nasua nasua*), with the total cost of eradicating all four species estimated to range between €0.45-2.25M (based on the sum of lower and upper bounds for the risk management component cost). The key eradication methods identified included netting, trapping, manual capture and shooting, which were not considered to cause significant adverse environmental, social or economic harm. Acceptability scores were high, except for *N. nasua*, which scored medium. The window of opportunity for all of these species was 1-3 years.

The ten high priority established species comprised three terrestrial plants, one freshwater plant, two terrestrial vertebrates, two freshwater animals, one insect and one marine tunicate (Table 5). These included species with primarily high overall risk and high overall feasibility of eradication scores; however, two species scored very high risk with only medium feasibility (alligator weed, *Alternanthera philoxeroides*; and the marine tunicate, *Botrylloides giganteum*). Invasion scenarios suggested that the majority of high priority species were relatively well confined comprising 1-3 populations, although three plants had more (10-50 populations) as did the oriental weather-fish, *Misgurnus anguillicaudatus* (10-50 populations) and the apple tree-borer, *Saperda candida* (4-10 populations). The area covered by these species was thought to range from <1 ha (common yabby, *Cherax destructor*; and *B. giganteum*) to >100 km^2 (Indian spotted deer, *Axis axis*) and they were present in seven EU Member States, including: Italy (3), France (3), Germany (3), Spain (2), Croatia (1), United Kingdom (1) and Netherlands (1). The cost range for eradicating all ten species was in the region of €1M-5.5M. Barriers to eradication were identified for some species. For example, the eradication of *M. anguillicaudatus* using electrofishing, fyke netting and piscicide was considered likely to cause moderate adverse environmental harm as well as low acceptability. Both *Rhea americana* (greater rhea) and *A. axis* received only medium acceptability scores; while the removal of *Ligustrum sinense* (Chinese privet) using mechanical means and herbicide had the potential to cause adverse environmental impacts. The window of opportunity for all of the ten high priority species was 1-3 years, except *B. giganteum* which had a very short window of opportunity (<2 months) and *A. axis* with a longer window (4-10 years).

Prevention and long-term management priorities

Where a species that has not yet established poses a high overall risk, but overall feasibility of eradication on detection is low, it is likely to be a priority for prevention. Three species were identified as particularly important for prevention based on very high overall risk and low or very low scores for overall feasibility of eradication: *Plotosus lineatus* (striped eel catfish), *Homarus americanus* (American lobster) and *Codium parvulum* (a green algae) (Figure 2a; Table S1).

For already established species with low scores for overall feasibility of eradication, long-term management (e.g. containment, slowing spread, control) may be a high priority. Eleven species were identified as potentially high priorities for long-term management on this basis (Figure 2b; Table S2). Three scored very high overall risk and very low overall feasibility of eradication, including *Arthurdendyus triangulatus* (New Zealand flatworm), *Pterois miles* (lion fish) and *Penaeus aztecus* (northern brown shrimp). The remaining eight species scored high overall risk and very low overall feasibility of eradication or very high overall risk and low overall feasibility, including: two marine invertebrates (a hydroid, *Macrorhynchia philippina*; and a polychaete, *Pseudonereis anomala*), three freshwater invertebrates (Chinese mystery snail, *Bellamya chinensis*; golden apple snail, *Pomacea canaliculata*; and giant apple snail, *Pomacea maculata*), one terrestrial invertebrate (a parasitic nematode, *Ashworthius sidemi*) and two terrestrial vertebrates (Finlaysons squirrel, *Callosciurus finlaysonii*; and small Asian mongoose, *Herpestes auropunctatus*).

Discussion

We identified priorities for the eradication of new and emerging IAS in Europe using a structured risk management tool combined with risk assessment scores derived from horizon scanning. This exercise not only indicated priorities for the eradication of emerging species and contingency planning for new species, but potential priorities for prevention and long-term management as well. While the NNRM has previously been applied at regional and national scales (Adriaens *et al.*, 2019, Booy *et al.*, 2017, Osunkoya *et al.*, 2019), this is the first application across multiple countries. Despite increased complexity at this scale and a lack of information on the status of some species in Europe, we found that the scheme could be applied successfully at a continental scale.

Although the species-specific eradication feasibility scores resulting from this exercise provide support for those taking decisions about how and which IAS to manage, they are not straightforward management recommendations. The feasibility scores are linked to specific invasion scenarios and eradication strategies, which are subject to knowledge gaps and change, for example as a result of changes in species distributions and new eradication methods becoming technically or legally available.

As with other screening methods (including horizon scanning, rapid risk assessment and hazard identification), the results should be considered preliminary and subject to further in-depth assessment. For example, detailed management plans would need to be drafted to implement the management priorities identified here and these should include further assessment in the field to confirm population sizes and distribution as well as the applicability of management methods. These need to accommodate for alternative strategies if eradication actions do not obtain the expected result (Gregory *et al.*, 2012, Richardson *et al.*, 2020). Careful planning is necessary to evaluate the effort needed for eradication, which can be supported by modelling (e.g. Tattoni *et al.*, 2006). Further tools for in-depth assessment of the initial priorities identified here could include the use of cost-benefit analysis, cost-effectiveness analysis and eradication probability modelling (Drolet *et al.*, 2015).

We assessed high and very high risk IAS identified by horizon scanning as these are likely candidates for prevention, early detection and rapid eradication given their absence or limited status in the EU (Roy *et al.*, 2015). They are also of particular concern currently in the EU which has recently adopted regulation 1143/2014 on IAS that emphasises the importance of prevention and rapid eradication (EU, 2014). While horizon scanning provides a useful method for reducing long lists of potentially thousands of species to a shorter list of those most likely to be threats (Peyton *et al.* 2019, Roy *et al.*, 2015), it is of limited use for prioritising specific actions as it does not take into account the feasibility of management (Booy *et al.*, 2017, Vanderhoeven *et al.*, 2017). By applying risk management criteria, our study refined this list into specific management priorities, aligning with the guiding three step hierarchical approach of IAS management set out in the Convention on Biological Diversity (UNEP, 2011).

The results of this study demonstrate the value of incorporating both risk assessment (here derived from horizon scanning) and risk management criteria when prioritising IAS. There was no correlation between eradicating feasibility and risk assessment scores, indicating that risk management criteria evaluate information that is different to risk assessment. This additional information is an essential part of risk analysis, and fundamental to decision-makers, who must take into account a wide range of criteria that go beyond risk (Dana *et al.*, 2014, Kerr *et al.*, 2016, Simberloff, 2003). While risk management is traditionally included along with risk assessment as part of an overall approach to risk analysis in other disciplines, such as plant health, animal health and food safety (EFSA, 2010, OiE, 2017, Ahl *et al.*, 1993, FAO, 2013) it has rarely been applied so systematically to IAS. This is particularly true in Europe, where risk assessment alone has been the dominant method used to support prioritisation (Essl *et al.*, 2011, Heikkilä, 2011, Kerr *et al.*, 2016, Roy *et al.*, 2018, Turbé *et al.*, 2017, Vanderhoeven *et al.*, 2017). Our results highlight the importance of incorporating this step and, by doing so, identifying refined priorities more specifically linked to management outcomes.

Modifying the NNRM scheme by standardising invasion scenarios, based on the number of discrete populations and total combined area of all populations, allowed us to explore the feasibility of eradication at different spatial scales. Across all environments the overall feasibility of eradication decreased as extent increased, which reflects the fact that elements of feasibility, such as cost and resource effort, are known to scale with extent (Brockerhoff *et al.*, 2010, Howald *et al.*, 2007, Rejmánek & Pitcairn, 2002, Robertson *et al.*, 2017).

Terrestrial species received highest scores for overall feasibility of eradication, followed by freshwater species and then marine species, which reflects the different challenges of eradication in these different environments (Booy *et al.*, 2017). While the feasibility of eradicating terrestrial species was highest at smaller scales, it remained high even at larger scales, albeit with reduced confidence. Indeed, successful eradications on large land masses have been reported in Europe of invasive mammals and birds (Robertson *et al.*, 2015, Robertson *et al.*, 2017). In contrast, the feasibility of eradicating freshwater species was likely to be feasible at small scales (i.e. few populations <1-3, or small area <1ha), but unlikely to be feasible at larger scales (i.e. > 1-3 populations and >1ha). In the marine environment, feasibility was likely to be low, even at small extents. These results indicate that extent alone is not a good predictor of feasibility when comparing species from different environments. They also suggest that early detection and rapid eradication is particularly important for freshwater species, for which action at an early stage of invasion considerably increases the likelihood that eradication will be feasible. This appears to be less important for terrestrial species, for which eradication remains feasible across considerably larger scales, and for marine species, for which eradication even at small scales is unlikely to be feasible in most circumstances. Of course, eradication is not the only rapid response measure that could be deployed, and these results do not preclude the possibility that early detection and rapid action to contain or slow the spread of a marine species may be useful.

We identified four species already established in Europe (i.e. emerging) as highest priorities for eradication: common myna, *Acridotheres tristis*; Berber toad, *Bufo mauritanicus*; coati, *Nasua nasua*; red-vented bulbul, *Pycnonotus cafer*. These are all terrestrial vertebrates with small population sizes and small areas, which reflects experience from Europe and elsewhere, where eradication campaigns have often targeted terrestrial vertebrates in small areas (Genovesi, 2005, Mayol *et al.*, 2009, Saavedra, 2010) and sometimes across wider extents (Robertson *et al.*, 2017). However, the next ten priorities represented a much wider range of taxa including plants, invertebrates and fish, suggesting there may be scope to widen the taxonomic range of attempted eradications in Europe. Our results indicate that eradication is not only feasible for the top fourteen species, but could be relatively inexpensive (total cost estimate to eradicate the top four established priority species with limited distributions in Europe was €0.45-2.25M, while total cost for the next ten species was €1-5.5M) in comparison to EU funding for other IAS projects (Scalera, 2009). However, although cost is a very important factor in the overall feasibility of eradication (Booy *et al.*, 2017), costing eradications is complex and comprehensive data on the cost of invasive species eradications are generally scarce (Adriaens *et al.*, 2015, Donlan & Wilcox, 2007) which warrants interpreting these crude ordinal cost estimates with caution. Also, the cost is very dependent on the specific invasion scenarios and management strategies drafted for this exercise. As the invasion extent of several species appeared poorly documented (e.g. *A. tristis*) or surrounded by considerable uncertainty (e.g. *B. mauritanicus*), costs could have been underestimated. Lastly, the extent of a species invasion can rapidly change. On the other hand, the cost for eradication could also be reduced by managing several co-occurring species with similar management approaches at once (Mill *et al.*, 2020). Such concrete cost estimates are beyond the broad scale feasibility assessment performed in our study.

Lower scores for some risk management components suggest potential barriers to eradication that would need to be overcome. These include the medium acceptability scores for eradicating the *N. nasua* (coati), *A. axis* (Indian spotted deer) and *R. americana* (greater rhea), which indicates a potential lack of public or stakeholder acceptance for this work on perceived animal welfare grounds. While acceptance of the use of herbicides could be a barrier to eradicating invasive non-native plants, this was not considered a significant problem for the plants included in the high priority lists. However, acceptability was a potential barrier for the eradication of *M. anguillicaudatus* (oriental weatherfish) because of potential public concern over the use of piscicides. Furthermore, the use of piscicides in public waters is prone to meet legal barriers in most European countries which is reflected in medium scores for practicality. Gaining access is a potential barrier to the eradication of some plant species, especially where they grow in difficult terrain. This was the case for *Euonymus fortunei,* which received a low practicality score because the most likely invasion scenario included the potential for its establishment on cliff edges. While these barriers are challenging and would have to be addressed as part of an eradication strategy, they were not considered insurmountable by the assessors.

Of the new (i.e. not yet established) species assessed, 43 were identified as potential priorities for eradication on arrival, although 17 were particularly high priority (highest and very high). Different priority species could establish in almost any region of Europe and would require a quick (<1 year) response to ensure the response was effective and reduce cost in the long term. Response teams would need to be capable of using a wide range of management techniques, with 13 broad eradication techniques identified for the top 17 high priority species. Indeed, for rapid eradication of new IAS in Europe to be effective, our results indicate coordination across European countries would be key to encourage the development and timely deployment of the plans. This would require countries to agree on priority species and to maintain access to response teams with a broad range of management expertise and capacity, which may be lacking in some cases. Contingency planning may help to address these issues and can help ensure rapid eradication is delivered effectively and efficiently, by agreeing in advance the roles, responsibilities and resources that will be used to respond to a new incursion before it happens. The priority species identified here would be good candidates for Europe wide IAS contingency planning.

While the main role of the NNRM is to identify priorities for eradication and contingency planning, it also identifies potential priorities for long-term management and prevention. Long-term management is likely to be a priority for established species where the overall feasibility of eradication is low and the overall risk is high. For example, the feasibility of eradicating *Arthurdendyus triangulatus* (New Zealand flatworm) was considered very low, but it may be feasible to slow the spread of this species using phytosanitary measures (Boag & Yeates, 2001). Similarly, the NNRM can identify potential prevention priorities for species that are not yet established where the feasibility of eradication is low and the risk high. For example, should *Homarus americanus* (American lobster) establish in European waters it is unlikely that eradication would be feasible and so prevention, perhaps by tightening control of its release and escape pathways (Jørstad *et al.*, 2011, van der Meeren *et al.*, 2016), should be considered a particularly high priority.

A limitation of the NNRM is that it does not currently evaluate the effectiveness of long-term management (e.g. containment, slowing spread, control) or prevention measures. This is important because long-term management may not always be feasible for species that cannot be eradicated. For example, long-term management may not have a lasting impact on the spreading population of *Pterois miles* (lion fish) in Europe, despite calls for its consideration (Kletou *et al.*, 2016). Similarly, prevention may not always be feasible, as is likely to be the case for *Plotosus lineatus* (striped eel catfish) which seems set to establish in EU waters following its arrival through the Suez Canal (Edelist *et al.*, 2012). Where considering future prevention and long-term management priorities these factors need to be taken into account and this is a priority for further development of the NNRM.

The approach to prioritisation presented here has application for IAS policy and management. Our results help focus more attention on the eradication of species with limited distributions and contingency planning for new arrivals where this is feasible. The availability of management methods, expected environmental non-target effects and the proportionality of the benefits and costs of eradication are important elements in the current decision making on IAS management in Europe (EU, 2014). These elements of risk management are considered in our assessment and cannot be provided by risk assessment alone. Our approach thus helps to address these, including providing a method to assess the feasibility of eradication, supporting the development of management plans and evaluating the potential benefits of listing under the EU IAS regulation.

To date, there is no agreed method for determining whether eradication is feasible and so application is likely to be subjective and potentially inconsistent across Europe. Listing alone may not be sufficient to drive EU wide eradication and contingency planning for species identified as priorities. Other mechanisms may be needed to do this, for example specific eradication and contingency planning programmes under the EU LIFE funding stream. Such programmes would need to be coordinated across Europe and would benefit from sharing of expertise. While our results are focused on the European situation, the procedure here developed could be used in other part of the world to implement or improve strategies to limit the impact of IAS.

As numbers of IAS are predicted to increase and global management targets become more ambitious, transparent methods for prioritising action are essential. We recommend that the structured assessment of risk management criteria, such as those included within the NNRM scheme, be applied routinely to IAS, as is commonplace in other biosecurity areas. While there are increasing calls for the application of risk assessment to more species (Carboneras *et al.*, 2018), we suggest that there should be at least as great a focus on evaluating the feasibility of management in a future with increasingly limited resources for nature conservation.

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Data Sharing and Data Accessibility

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.8pk0p2nk1 (Booy *et al.,* 2020).

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Table 1. Count of species by environment, establishment status in the EU and broad taxonomic group

Environment	Status	Plant	Vert	Invert	∑
Freshwater	Established	1	3	5	9
	Not established	0	10	4	14
Terrestrial	Established	6	10	4	20
	Not established	17	11	9	37
Marine	Established	0	1	5	6
	Not established	2	1	6	9
∑		26	36	33	

Table 2. Count of species by scenario code for extent.Letters A-D represent the number of discrete populations (respectively 1-3, 4-10, 10-50, +50) and numbers 1-6 represent total combined area (respectively <1ha, 1-10ha, 10ha-1km^2, 1-10km^2, 10-100km^2, >100km^2). For example, the code B2 indicate a species with 4-10 populations covering a total area 1-10ha.

		Area					
		1	**2**	**3**	**4**	**5**	**6**
Populations	**A**	22	23	3	5	5	2
	B	1	11	2	0	1	4
	C	1	6	3	1	0	1
	D	0	2	0	1	0	1

Table 3. Priority matrix based on risk assessment scores (derived from horizon scanning) and scores for overall feasibility of eradication (derived from this risk management exercise). Only high and very high risk species were included in this study (hence it was not possible for species to be placed in greyed out parts of the matrix). The matrix indicates priorities for eradication (background colour and cell text). Potential priorities for prevention and long term management are marked + (high) and ++ (highest priority).

Overall risk assessment score (derived from horizon scanning)	Overall feasibility of eradication (derived from this exercise)				
	Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Very high (5)	Medium++	Medium-high+	High	Very high	Highest
High (4)	Medium-low+	Medium	Medium-high	High	Very high
Medium (3)	Low	Medium-low	Medium	Medium-high	High
Low (2)	Very low	Low	Medium-low	Medium	Medium-high
Very low (1)	Lowest	Very low	Low	Medium-low	Medium

Figure 1. Cumulative Link Model predictions for the overall feasibility of eradication in different environments at different spatial scales. The probability of the overall feasibility of eradication being each of the five response levels very high (VH) to very low (VL) is given (on the y axis) for each combination of variables, with 95% confidence intervals. Note that colours indicate feasibility of eradication (green = higher feasibility, red = lower feasibility), these are different to those used (e.g. in Table 5.3) to indicate priority (where red = higher priority and green = lower priority).

[file uploaded separately]

Figure 2. Counts of species within the priority matrix for (a) new and (b) emerging species. The colour of the matrix reflects priority (derived from Table 3) ranging from highest (top right) to lowest (bottom left) priority. Note that species were not included in this study with lower than high overall risk assessment scores and so no species occupy the bottom three rows of each table. VL = very low, L = low, M = medium, H = high, VH = very high.

a. new species (priorities for prevention are marked highest^{++} and high^{+})

New species			Feasibility of eradication				
			VL	L	M	H	VH
			1	8	11	30	10
Risk score	VH	14	1^{++}	2^{+}	3	7	1
	H	46	0^{+}	6	8	23	9
	M	0	-	-	-	-	-
	L	0	-	-	-	-	-
	VL	0	-	-	-	-	-

Species listed in priority order:

Highest- *Faxonius rusticus*. **Very high**- *Bison bison, Channa argus, Cryptostegia grandiflora, Gambusia affinis, Lampropeltis getula, Lonicera morrowii, Micropterus dolomieu, Misgurnus mizolepis, Oreochromis aureus, Oreochromis mossambicus, Oreochromis niloticus, Pachycondyla chinensis, Rubus rosifolius, Sirex ermak, Solenopsis invicta, Trichosurus vulpecula*... **High-** *Aeolesthes sarta, Albizia lebbeck, Amynthas agrestis, Boiga irregularis, Celastrus orbiculatus, Cherax quadricarinatus, Chromolaena odorata, Chrysemys picta, Cinnamomum camphora, Clematis terniflora, Crepidula onyx, Cyprinella lutrensis, Eleutherodactylus coqui, Gymnocoronis spilanthoides, Limnoperna fortunei, Lonicera maackii, Mytilopsis sallei, Prosopis juliflora, Prunus campanulata, Pycnonotus jocosus, Rhinella marina, Solenopsis geminata, Tetropium gracilicorne, Tilapia zillii, Triadica sebifera, Vespula pensylvanica*.. **Medium-high-** *Acanthophora spicifera, Cortaderia jubata, Cynops pyrrhogaster, Hemidactylus frenatus, Lygodium japonicum, Microstegium vimineum, Solenopsis richteri, Symplegma reptans, Codium parvulum*$^{+}$, *Homarus americanus*$^{+}$. **Medium -** *Eleutherodactylus planirostris, Gammarus fasciatus, Lespedeza cuneata, Morone americana, Perna viridis, Potamocorbula amurensis, Plotosus lineatus*$^{++}$

b. emerging species (priorities for long-term management are marked highest^{++} and high^{+})

Emerging species			Feasibility of eradication				
			VL	L	M	H	VH
			7	8	8	12	0
Risk	VH	13	3^{++}	4^{+}	2	4	0

Species listed in priority order:

Very high - *Acridotheres tristis, Bufo mauritanicus, Nasua nasua, Pycnonotus cafer*. **High -** *Alternanthera philoxeroides, Axis axis, Botrylloides giganteum, Cherax destructor, Euonymus fortunei, Euonymus japonicus, Ligustrum sinense, Misgurnus anguillicaudatus, Rhea americana, Saperda candida*. **Medium-high -** *Andropogon virginicus, Ehrharta calycina, Fundulus heteroclitus, Hypostomus plecostomus, Marisa cornuarietis, Wedelia trilobata, Callosciurus finlaysonii*$^{+}$, *Herpestes auropunctatus*$^{+}$, *Pomacea canaliculata*$^{+}$, *Pomacea maculata*$^{+}$. **Medium -** *Acridotheres cristatellus, Charybdis japonica, Pheidole megacephala, Psittacula eupatria, Arthurdendyus triangulatus*$^{++}$, *Penaeus aztecus*$^{++}$, *Pterois miles*$^{++}$. **Medium-low -** *Ashworthius sidemi*$^{+}$, *Bellamya chinensis*$^{+}$, *Macrorhynchia philippina*$^{+}$, *Pseudonereis anomala*$^{+}$.

score	H	22	4^+	4	6	8	0
	M	0	-	-	-	-	-
	L	0	-	-	-	-	-
	VL	0	-	-	-	-	-

Table 4. Highest and very high priorities for the eradication of new species (i.e. not yet established) following arrival in Europe.

Priority	Scientific name	English name	RA	RM	Conf	Scen	Regions	Eradication method	Effect.	Pract.	Cost min (1000s)	Cost max (1000s)	Impact	Accept.	Window	Reinv.
Highest	*Faxonius rusticus*	rusty crayfish	VH	VH	M	A1	MED, ATL, CON, STE	trapping	v. high	high	€ 1	€ 50	minimal	v. high	2m-1yr	high
Very high	*Bison bison*	American bison	H	VH	H	A4	CON	shooting	v. high	high	€ 1	€ 50	minimal	high	4-10yrs	v. low
Very high	*Channa argus*	northern snakehead	VH	H	M	A2	MAC, MED, ATL, CON, STE	electrofishing, fyke netting	v. high	v. high	€ 50	€ 200	minimal	v. high	2m-1yr	medium
Very high	*Cryptostegia grandiflora*	none	H	VH	H	A1	MAC, ATL, MED	mechanical, herbicide	v. high	v. high	€ 1	€ 50	minimal	v. high	1-3yrs	high
Very high	*Gambusia affinis*	western mosquitofish	VH	H	H	A2	MAC, MED, ATL, CON, STE	piscicide	v. high	medium	€ 50	€ 200	minor	medium	<2m	medium
Very high	*Lampropeltis getula*	common kingsnake	VH	H	M	A4	MAC, MED	manual, trapping	high	medium	€ 200	€ 1,000	minimal	v. high	1-3yrs	low
Very high	*Lonicera morrowii*	morrow's honeysuckle	H	VH	M	A2	ATL, CON, MAC, MED	manual, herbicide	v. high	high	€ 1	€ 50	minor	v. high	1-3yrs	medium
Very high	*Micropterus dolomieu*	smallmouth bass	VH	H	M	A1	MAC, MED, ATL, CON, STE	fyke netting, electrofishing	high	high	€ 50	€ 200	minor	high	2m-1yr	high
Very high	*Misgurnus mizolepis*	Chinese weather loach	H	VH	H	A1	MAC, MED, ATL, CON, STE	draining, piscicide	v. high	v. high	€ 1	€ 50	minimal	v. high	2m-1yr	low
Very high	*Oreochromis aureus*	blue tilapia	VH	H	H	A2	MAC, MED	netting, angling	high	high	€ 50	€ 200	minimal	high	1-3yrs	medium
Very high	*Oreochromis mossambicus*	Mozambique tilapia	VH	H	H	A2	MAC, MED	draining, piscicide	v. high	high	€ 1	€ 50	minimal	v. high	2m-1yr	medium
Very high	*Oreochromis niloticus*	Nile tilapia	VH	H	H	B2	MAC, MED	draining	v. high	high	€ 1	€ 50	minimal	v. high	1-3yrs	low

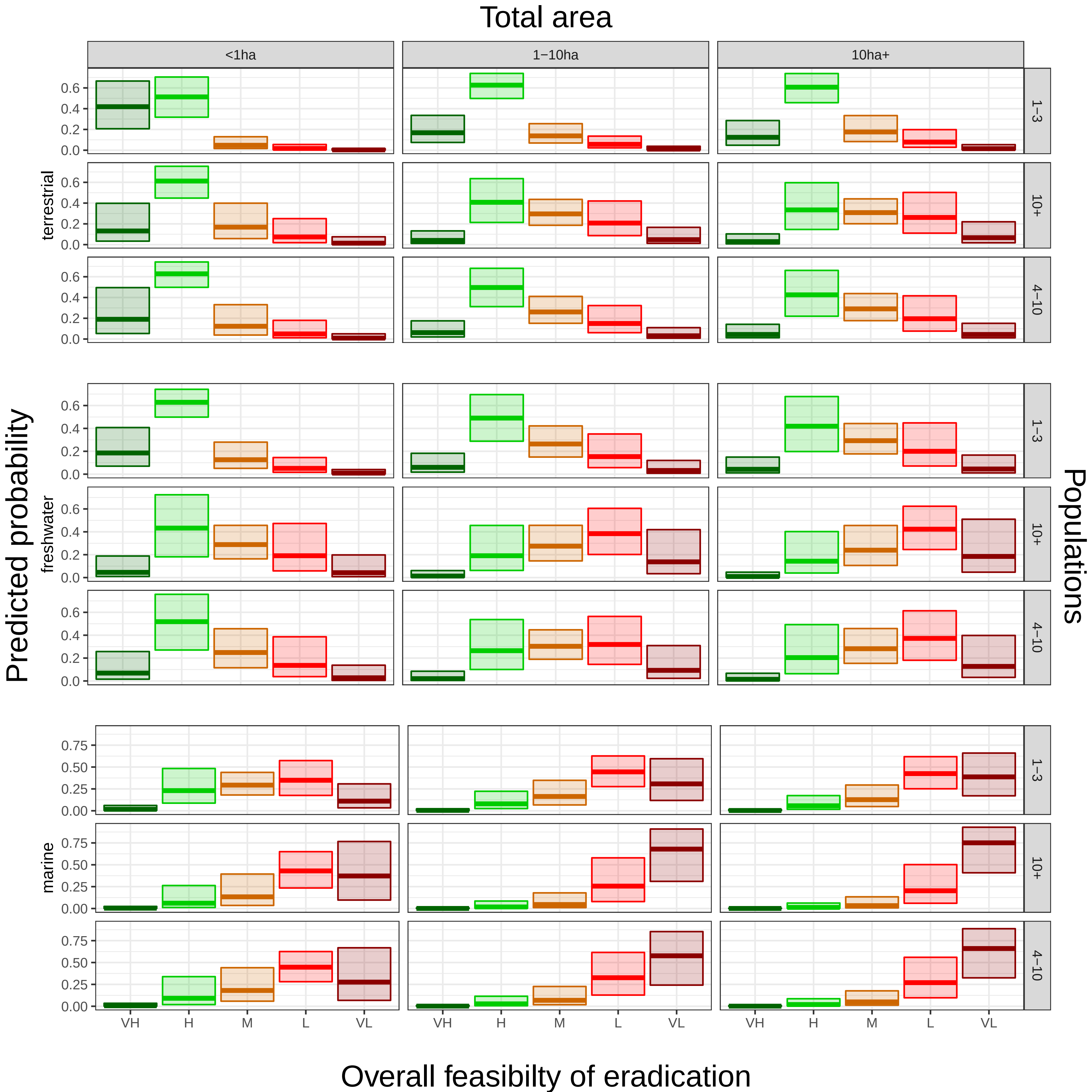
Very high	*Pachycondyla chinensis*	Asian needle ant	H	VH	M	B1	MED, ATL, CON, STE, MAC	baiting, insecticide	v. high	high	€ 1	€ 50	minimal	v. high	2m-1yr	medium
Very high	*Rubus rosifolius*	roseleaf bramble	H	VH	M	A1	MAC	manual, herbicide	high	v. high	€ 1	€ 50	minimal	high	2m-1yr	low
Very high	*Sirex ermak*	blue-black horntail	H	VH	H	A1	CON, STE, BOR	incineration	v. high	v. high	€ 50	€ 200	minimal	v. high	<2 m	medium
Very high	*Solenopsis invicta*	red imported fire ant	H	VH	M	A1	MAC, MED	poison baiting	v. high	v. high	€ 1	€ 50	minimal	v. high	2m-1yr	high
Very high	*Trichosurus vulpecula*	brushtail possum	H	VH	H	A4	ATL, MED, CON, MAC	trapping	v. high	v. high	€ 50	€ 200	minimal	high	1-3yrs	v. low

Abbreviations: priority = priority for eradication (refer to Table 3); RA = overall risk, RM = overall feasibility of eradication, conf. = confidence rating (VH = very high, H = high, M = medium, L = low, VL = very low); scen. = scenario code (refer to Table 2); regions = threatened biogeographic regions within the EU (ALP = Alpine Region, BOR = Boreal Region, ATL = Atlantic Region, CON = Continental Region, MED = Mediterranean Region, MAC = Macaronesian Region, STE = Steppic Region, BLK = Black Sea Region); effectiveness, practicality, cost (minimum bound), cost (maximum bound), impact, acceptability, window of opportunity (m = month, yr = year) and likelihood of re-invasion.

Table 5. Very high and high priorities for eradication of established species (i.e. established with limited distribution) in Europe. For abbreviations refer to Table 4; MS = EU Member States in which the species is thought to be established.

Priority	**Scientific name**	**English name**	**RA**	**RM**	**Conf**	**Scen**	**MS**	**Eradication methods**	**Effect.**	**Pract.**	**Cost min (1000s)**	**Cost max (1000s)**	**Impact**	**Accept.**	**Window**	**Reinv.**
Very high	*Acridotheres tristis*	common myna	VH	H	H	A5	ES, PT	netting, trapping, shooting	high	medium	€ 200	€ 1,000	minimal	high	1-3yrs	medium
Very high	*Bufo mauritanicus*	Berber toad	VH	H	M	A2	ES	manual capture, netting	high	medium	€ 1	€ 50	minor	v. high	1-3yrs	low
Very high	*Nasua nasua*	coati	VH	H	M	A4	ES	trapping, shooting	high	high	€ 200	€ 1,000	minimal	medium	1-3yrs	low
Very high	*Pycnonotus cafer*	red-vented bulbul	VH	H	H	A5	ES	trapping, netting	high	high	€ 50	€ 200	minimal	high	1-3yrs	medium
High	*Alternanthera philoxeroides*	alligator-weed	VH	M	M	C2	FR, IT	mechanical, manual	medium	high	€ 200	€ 1,000	minor	high	1-3yrs	medium
High	*Axis axis*	Indian spotted deer	H	H	H	A6	CR	shooting, sterilization	high	high	€ 200	€ 1,000	minor	medium	4-10yrs	low
High	*Botrylloides giganteum*	none	VH	M	M	A1	IT	wrapping structures	medium	high	€ 200	€ 1,000	minor	high	<2 m	high
High	*Cherax destructor*	common yabby	H	H	M	A1	ES	biocontrol, trapping	high	high	€ 1	€ 50	minimal	v. high	1-3yrs	high
High	*Euonymus fortunei*	winter creeper	H	H	H	A2	FR	herbicide	high	low	€ 50	€ 200	minor	high	1-3yrs	high
High	*Euonymus japonicus*	Japanese spindle	H	H	M	B2	UK	grubbing, mechanical, herbicide	high	high	€ 1	€ 50	minor	v. high	1-3yrs	high
High	*Ligustrum sinense*	Chinese privet	H	H	M	B2	FR	grubbing, mechanical, herbicide	high	high	€ 1	€ 50	moderate	v. high	1-3yrs	medium

High	*Misgurnus anguillicaudatus*	oriental weatherfish	H	H	H	C4	NL, DE, ES, IT	electrofishing, piscicide, fyke netting	v. high	medium	€ 200	€ 1,000	moderate	low	1-3yrs	medium
High	*Rhea americana*	greater rhea	H	H	M	A5	DE	shooting, and other methods	v. high	high	€ 200	€ 1,000	minor	medium	1-3yrs	medium
High	*Saperda candida*	apple tree borer	H	H	H	B2	DE	manual destruction, felling of trees	high	high	€ 1	€ 50	minor	high	1-3yrs	medium


Total area
<1ha
1−10ha
10ha+
terrestrial
freshwater
marine
1−3
10+
4−10
Populations
Predicted probability
0.0
0.2
0.4
0.6
0.00
0.25
0.50
0.75
VH
H
M
L
VL
Overall feasibilty of eradication