PRATIQUE

ENHANCEMENTS OF PEST RISK ANALYSIS TECHNIQUES

Review of eradication and containment campaigns

PD No. 5-1

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Submission date:

EU Framework 7 Research Project
Enhancements of Pest Risk
Analysis Techniques

(Grant Agreement No. 212459)

SEVENTH FRAMEWORK PROGRAMME

PROJECT OVERVIEW: PRATIQUE is an EC-funded 7th Framework research project designed to address the major challenges for pest risk analysis (PRA) in Europe. It has three principal objectives: (i) to assemble the datasets required to construct PRAs valid for the whole of the EU, (ii) to conduct multi-disciplinary research that enhances the techniques used in PRA and (iii) to provide a decision support scheme for PRA that is efficient and user-friendly. For further information please visit the project website or e-mail the project office using the details provided below:

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Disclaimer:

This publication has been funded under the small collaborative project PRATIQUE, an EU 7th

Framework Programme for Research, Technological Development and Demonstration addressing theme: [kbbe-2007-1-2-03: development of more efficient risk analysis techniques for pests and pathogens of phytosanitary concern call: fp7- kbbe-2007-1]. Its content does not represent the official position of the European Commission and is entirely under the responsibility of the authors. The information in this document is provided as is and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and liability.

Table of Contents:

Summary

Eradication of invasive alien plant pests involves the application of phytosanitary measures to eliminate them from an area, when measures to prevent their entry have failed. National plant protection organisations (NPPOs) may also rely solely on surveillance and eradication as risk mitigation measures. However, whilst the eradication of an organism usually is the initial goal of phytosanitary services it is not the only strategy available (others being containment or suppression). NPPOs need to decide which measures to apply if and when a quarantine pest is found in an area. Until now, no generic decision support scheme has existed to help NPPOs in outbreak situations. The aim of this deliverable therefore, was to collect information on eradication campaigns against plant pests and invasive alien plants and to investigate which factors were related to successful outcomes. The results of this analysis will be integrated into the decision support scheme that is being developed in task 5.3 of PRATIQUE. We collected data on 171 different campaigns (eradications, containments and suppressions) against 102 species and applied two different analytical methods to analyse the dataset. 1) Linear mixed effect models (LMEs) were used to test a few often-stipulated factors relevant for eradication success, such as the spatial extent of an outbreak, the importance of quick reaction times, the cooperation between stakeholders, the readiness of NPPOs to act after an outbreak and the pest category (insects, plants or pathogens). Indoor eradications and the readiness to act after an outbreak were relevant factors in the model, together with the information that pathogens are more difficult to eradicate than insects. 2) A more extended analysis was performed using classification and regression trees (CART). This analysis included more factors and revealed that both the accessibility and the size of an infested area are significantly related to successful eradication outcomes. Furthermore, the pest category and spreading capacity of the harmful organism are decisive for the overall success of a campaign. Overall, the classification tree analysis suggests that eradication campaign may be successful if the infested area is accessible and not larger than approx. 4,000 ha and if the organism is not a fungus. We propose evaluating the usefulness of these factors for a generic decision support scheme in task 5.3 of the PRATIQUE project. This task aims at improving the evaluation of risk management options in the EPPO scheme in order to guide actions that should be taken at pest outbreaks.

General introduction

To avoid negative impacts from invasive alien species (IAS) it is best to prevent their entry (Touza *et al.*, 2007). Yet it is unrealistic to expect exclusion measures to be 100% effective and policies for preventing invasions must include monitoring and control measures, if necessary. If therefore, a quarantine organism is intercepted, pest risk managers need to take appropriate measures to prevent the organism from establishing and spreading. It is argued that once prevention has failed and an alien species is detected, eradication is the best alternative, considering the mounting costs and undesired effects related to permanent control or to a “do-nothing”-policy (Genovesi, 2007), but see also Olsen & Roy (2002). An ideal eradication campaign would destroy all individuals of a potentially invasive species immediately upon their arrival (Mack & Lonsdale, 2002). This is however, rarely possible, since biological invasions often go undetected in the early stages, by virtue of the fact that nearly all incipient invasions consist of a small number of sparsely distributed organisms (Carey, 1996). Nevertheless, maximum effort should be focused on small, isolated outbreaks, a policy which requires an effective early-warning/rapid response capability (Simberloff, 2008).

Eradication is the application of phytosanitary measures to eliminate a pest from an area (FAO, 1998). This measure has often proven to be successful, if taken at an early stage of the invasion process (Myers *et al.*, 1998, Rejmánek & Pitcairn, 2002, Simberloff, 2003, Simberloff, 2008). However, complete elimination is not always feasible, especially in budget-limited situations or where eradication is not possible due to the biology or the mobility of the organism or if re-introductions are very likely. In such situations, a containment or suppression strategy might be more efficient measures to control a new pest (Baxter *et al.*, 2008). In other words, a pest may be established in a limited area, but is contained within that area by the application of official measures. The gypsy moth slow the spread-campaign in the US is an example of such a containment campaign (http://www.gmsts.org/operations/index.htm). Pest managers need tools to evaluate costs and benefits of a management measure as accurately as possible to secure necessary resources for eradication and to apply cost effective and appropriate measures. This requires that the efficacy of a given measure should be also assessed.

In the EU, EC directives describe measures to be taken following outbreaks of a few well known quarantine pests, e.g. for the Western corn rootworm *Diabrotica virgifera virgifera* (EC, 2000, EC, 2003). There are international standards such as the International Standard for Phytosanitary Measures No. 9 (‘Guidelines for pest eradication programmes’) to prevent the introduction and/or spread of quarantine pests. The European and Mediterranean Plant

Protection Organization EPPO has adopted a regional standard describing which elements should be addressed in contingency plans (EPPO, 2009). However, there is no generic decision support scheme to help guide eradication or containment actions for all quarantine pests, whatever the pest, the habitat or the extent of the outbreak when first discovered (Baker *et al.*, 2009). PRATIQUE aims at developing scientifically based decision support scheme for risk managers of plant pests in the EU.

In the recent past, there have been a number of reviews of eradication attempts (Myers *et al.*, 2000, Simberloff, 2003, Genovesi, 2005, Simberloff, 2009). Many refer to case histories from a wide range of organisms, often encompassing insects, pathogens, marine or terrestrial plants, vertebrates, and molluscs, to draw general conclusions about the factors that lead to successful eradication (Myers *et al.*, 1998, Simberloff, 2003). Furthermore, distinct ecosystems (i.e. marine, terrestrial, agricultural, forests) are compared in an attempt to understand why an eradication campaign failed or succeeded (Myers *et al.*, 2000, Simberloff, 2003, Simberloff, 2009). A recent review by Simberloff (2009) lists the factors believed to be crucial for successful eradication: these are (1) early detection and quick reaction, (2) sufficient resources, (3) clear legal authorisation, (4) sufficient knowledge about the organism and (5) an energetic project management team. These factors were nevertheless, largely derived from anecdotal eradication reports, without statistical analysis. Genovesi (2005) did a more systematic review that was restricted to eradications in Europe. He concluded that in Europe no records exist on eradications against alien invertebrates or marine organisms and that only some very localized removals of alien plants have been attempted in Europe. His review thus included only alien vertebrates in Europe and he also did not analyse his data statistically (Genovesi, 2005). As it happens there have been successful eradications of alien invertebrate pests in Europe; for instance the United Kingdom has eradicated the Colorado beetle, *Leptinotarsa decemlineata*, 163 times (Bartlett, 1979) and melon thrips, *Thrips palmi* was successfully eradicated from UK glasshouses (Cannon *et al.*, 2007). We are not aware of any attempt in the literature, to statistically analyse factors associated with eradication success, but we think that new analytical tools such as classification trees and mixed effect models can help us to draw general conclusions about the successes and failures of eradication attempts. While most reviews mention plant pests, we are not aware that they have ever been addressed specifically in a review. This study aims at filling this knowledge gap. We are also not aware of any other study giving a general overview of eradication attempts targeted at plant pests or even systematically collating data on a wide range of plant pests and evaluating eradication campaigns against them. Invasive alien plants have also been the subject of eradication campaigns and Rejmánek & Pitcairn (2002) showed that professional eradications of small infestations (below one hectare) are usually possible.

In this review, we collected detailed data about as many plant pest eradications worldwide as possible as well as information on invasive alien plants. The review includes organisms defined as plant pests (EC, 2000), i.e. insects, nematodes, bacteria, fungi, viruses or viroids and invasive alien plants. An additional organism group (phytoplasma) was created for the European stonefruit yellows phytoplasma ESFYP, *Candidatus Phytoplasma prunorum* (Species group 16SrX, Apple proliferation group) (http://www.uniprot.org/taxonomy/47565) that includes the organism listed as Apricot chlorotic leafroll mycoplasma in the Plant Health Directive (EC 2000).

The information collected about campaigns to eradicate and contain quarantine pests in the EU and worldwide is compared here and a subset of campaigns (explicit eradications) is analysed in order to identify factors common to successful campaigns.

Based on previous reviews, we hypothesize the following:

i) Pest populations with a limited spatial occurrence are more easily eradicated than large outbreaks, because intensive phytosanitary measures are more easily applied.

ii) Island and indoor (closed system) outbreaks are more easily eradicated than campaigns on mainland or in complex (outdoor) structured receptor habitats, because in the former cases spread of the organisms is limited, the infested area might be more easily delimited and the organisms are less likely to "escape" from phytosanitary measures (Clout & Veitch, 2002, Krajick, 2005).

iii) Early detection and a quick response will increase the chances of success, because founder populations prior to establishment and potential spread, are more at risk of extinction due to environmental and demographic stochasticity and Allee effects (Liebhold & Bascompte, 2003). Thus if a small population is targeted for eradication soon after its introduction, eradication success is expected to be higher. This hypothesis might thus correlate with hypothesis i)

iv) Campaigns against well-known organisms are more likely to succeed, because the weak points of the organism have been identified and effective control measures might therefore be more readily available. Likewise, good cooperation between authorities, the involvement of stakeholders and the availability of a contingency plan could be equally important for the success of the campaign. It will make the mode of action clear for everyone from the beginning and discussions about responsibilities, funding, severity of possible impacts and control measures, will less likely occur and hamper the progress of the eradication (Stokes *et al.*, 2006). It might also enable the pest managers to take more efficient control measures because less opposition is expected from a well-informed public. We assume here, that an elaborate contingency plan will also include a risk communication campaign, to allay concerns and objections.

Material & Methods

Data collection

We collated data on campaigns aimed at containing and eradicating a plant pest population from a defined area. We included containment and area-wide pest control, because they are an important measure taken against many phytosanitary relevant organisms (Vreysen, 2007). An extended questionnaire was established for the collection of species-specific (life-history traits, pest history, detectability, spreading abilities, feeding behaviour), location-specific (invaded habitat type, altitudinal range, continentality) and event-specific factors (spatial scale of outbreak, management measures, effort, stakeholder commitment, information availability, properties of the target population, pathway properties, timing). The detailed questionnaire can be consulted in Table 1. The information retrieved from the questionnaires was compiled into a database hereafter referred to as the eradication database.

We searched for data in the Internet, and for published scientific papers and unpublished eradication reports from national plant protection organisations. Information about eradication campaigns is often difficult to obtain, because they are only rarely published and often only available as ‘grey’ literature, or not publicly accessible. Thus, national and regional plant protection organizations are important sources of information and pest managers from NPPOs were contacted to provide examples and detailed information about eradication campaigns from their countries. Furthermore the applicability of the EC DG SANCO operated CIRCA data server is discussed in Appendix 1.

In summary, the Solidarity data was used to provide details for specific cases (e.g. monetary costs for measures against some pests) where there were data gaps in the eradication database and for comparative purposes where expert judgements were provided. Seven cases obtained from solidarity returns (Appendix 1) were already in the eradication database and the solidarity dossiers confirmed these inputs; for 3 cases information about monetary costs was added to the eradication database.

Data preparation

Since the eradication measures are likely to differ, at least in degree of application, from containment or suppression measures, we distinguished between these management goals. Therefore, separate analyses will be needed for each goal. Here, we briefly review all campaigns in the database but use only those campaigns clearly identified as eradications for hypothesis testing and to construct classification trees.

Success of a campaign = dependent variable

The degree of success of a campaign was determined at four levels and only for the subset of campaigns clearly declared as eradications.

- Level 0: The campaign failed because the organism established and the campaign was stopped or switched to containment or suppression
- Level 1: The organism could neither be eradicated nor contained but instead expands its geographical distribution; but nonetheless, the campaign continued with the objective to eradicate the organism.
- Level 2: The campaign was successful in containing the organism within a certain area and the population density had been reduced considerably. Or the success of the eradication campaign was likely, provided that no further findings will occur in the time frame relevant for the species. Therefore the campaign continues in the form of surveys until successful eradication can be officially declared.
- Level 3: The eradication was successful, which was confirmed by surveys over a time period relevant for the life-cycle of the and after that period, the campaign was stopped. We distinguished level 3 from level 2 to account for the fact that a considerable time period may be needed to determine whether a campaign has been successful or not (Rout *et al.*, 2009).

Affected systems

We classified the organism into four categories, according to whether it was considered a pest in i) "agriculture" (all annual and perennial outdoor and indoor agricultural and horticultural crops), ii) "forestry" (managed or unmanaged forests and tree plantations, excluding ornamental/urban trees) or iii) "ornamentals" (including ornamental/urban trees and flowers). If an organism was judged capable of causing ecological damage (such as reducing biodiversity or affecting ecosystem services), it was classified as iv) an "ecological" problem. A pest species can be included in more than one of these four categories. This categorisation was included for two reasons; i) the life-history strategies of pests may differ between categories and ii) each category concerns different stakeholder groups; both factors might affect the success of a campaign. For example, if a species is only an agricultural problem, it might be more easily eradicated if stakeholders (farmers) support the measures because they are in their own interest. Conversely, if an organism is also perceived as a forest/ornamental or even an ecological problem, additional stakeholder groups might intervene and hamper campaigns (Myers *et al.*, 2000, Garcia-Llorente *et al.*, 2008).

Hypotheses

i) Spatial scale

To account for the spatial aspect of an eradication campaign, we introduced a spatial variable. A small, isolated outbreak focus, for example a finding in an individual glasshouse or on a group of isolated trees was classified as "local". The classification "regional" stands for measures taken at a regional scale, but within a country. Such campaigns cover a larger area, usually including several outbreak foci. "Countrywide" campaigns were addressed against an organism across an entire country and always include several or many outbreak foci. For campaigns in the United States, Canada and Australia, measures affecting an entire state or province were also classified as "countrywide". This classification was also chosen assuming that campaigns within one country/state/province should be easier to manage than international campaigns because they fall under one jurisdiction only. If several countries (or states or provinces in the case of the USA, Canada or Australia) were collectively managing an organism, these large scale campaigns were classified as "international" endeavours.

ii) Continentality and character of target system

We distinguished whether a campaign was endeavoured on an island or on the mainland. Because the measures and the outcome of eradications are likely to depend on the characteristics of the infested habitat, we distinguished between campaigns that addressed a) exclusively protected systems (such as glasshouses), b) exclusively outdoor systems or c) included both protected and open systems.

iii) Timing

The time elapsing between the arrival of an organism and the beginning of management measures was counted in years for the LME analyses, and in months for the CART. If the arrival date was not known, the date when the first spread or the first impact was noticed, was used in the analysis.

iv) Readiness to act and cooperation

The degree of knowledge about the species and the readiness of authorities to eradicate an incursion was considered as follows: a) none; information about the species and possible management measures were collected and evaluated only after the incursion, b) low; pest alerts, pest notices or similar information were available when the pest was detected, c) medium; a PRA for the species or a generic contingency plan was available prior to incursion, d) high; a contingency plan against the species was available prior to incursion. As second variable, the degree of cooperation was tested as answered in the questionnaire (Table 1); none, existing, strong.

Analyses

The database was analysed with two different tools for the following reasons: Our database includes many factors that potentially affect the outcome of a campaign. All these factors could be tested individually, but we would loose statistical power because of repeated testing. Another issue are data gaps, which LMEs cannot handle so well. For these reasons, we tested a few often-stated factors with LMEs, to begin with. Then, we used a novel approach with Classification and Regression Tree (CART) analysis, without prior hypothesising to see what could be learnt from the eradication database. CART analysis is more flexible because it can handle data gaps by creating surrogates, thus it was possible, to include many more factors (with data gaps) in the CART than with LMEs. CART was applied to 'mine' our extensive eradication database for meaningful factors related to successful eradication campaigns, without *a priori* formulated hypotheses. CART enabled us to discover generalities that might otherwise have been omitted (or overlooked) if we had focused only on hypothesis testing. Furthermore CART can deal with complexities often found in ecological datasets such as nonlinear relationships, high-order interactions and missing values (De'ath & Fabricius, 2000). Despite these complexities, CART allows for easy graphical interpretation of complex results (De'ath & Fabricius, 2000).

Linear mixed effect models (LMEs) for hypotheses testing

The analyses to test our hypotheses were performed with 126 eradication campaigns, using LMEs. We used the lme function of the software R (Version 2.7.1; R Development Core Team 2008). The outcome of each campaign served as the dependent variable and the factors that we expected to affect the outcome were included as fixed factors in a multivariate analysis. Factors included in the full model were i) spatial scale at four levels; local, regional, countrywide, international, ii) continentality; island vs. mainland and open/closed character of the targeted system; closed vs. open vs. both, iii) time in years between arrival of an organism and beginning of management measures, iv) degree of knowledge about the species and readiness to fight an incursion; none, low, medium or high, as well as the level of coordination between involved parties; none, existing or strong. We also included an approximation of taxonomic relatedness with 3 levels as fixed factor: insects, pathogens (including bacteria, fungi, viruses, nematodes and phytoplasma) and plants. Because some eradication campaigns were undertaken against the same species, the outcome of these campaigns can be expected to be related, we corrected for this by including the species name as random factor into the model. The full model was then iteratively simplified by removing non-significant terms to produce a minimal adequate model in which all terms and interactions are significant. Model simplification was done by minimising Akaike's Information Criterion (AIC).

Classification and Regression Tree (CART) Analysis

Classification trees (Breiman et al., 1984) are deemed an appropriate statistical method for the analysis of our dataset. The reasons are their ability to handle missing data, their flexibility and robustness, invariance to monotonic transformations of predictor variables, their ability to use combinations of explanatory variables that are either categorical and/or numeric, their ability to deal with nonlinear relationships and high-order interactions, and, despite all these analytical difficulties, their capability to give easily understandable and interpretable results

(De'ath & Fabricius, 2000). Furthermore, CART provides an intuitive insight into the kinds of interactions between explanatory variables (De’ath & Fabricius, 2000). In our dataset, the success of an eradication campaign served as response variable, denominated as “yes” for successfully accomplished campaigns and “no” for all other campaigns. Environmental factors and species traits served as explanatory variables. Since some species had several records in the dataset, the effect of individual species was weighted by using the reciprocal of the number of records in the dataset for each species. For a detailed description of the factors considered for the CART and their distribution see Appendix 3.

Trees were constructed by binary recursive partitioning, with the default “Gini” impurity measure, in CART v. 6.0 (Breiman *et al.* 1984, Steinberg & Colla 1995). To determine the optimal tree, a sequence of nested trees of decreasing size, each of them being the best of all trees of its size, were constructed, and their resubstitution relative errors were estimated. Ten-fold cross-validation was used to obtain estimates of cross-validated relative errors of these trees. These estimates were then plotted against tree size, and the optimal tree chosen both based on the i) minimum cost tree rule, which minimizes the cross validated error (the default setting in CART v 6.0; Steinberg & Colla 1995, p. 43), and based on the (ii) 1–SE rule, which minimizes cross-validated error within one standard error of the minimum (Breiman et al. 1984). Following De’ath & Fabricius (2000), a series of 50 cross-validations based on both rules were run, and the modal (most likely) single optimal tree was chosen for description. Using the weighted values for each species, the minimum size of each terminal node was limited to one. The quality of the best single classification tree was expressed as the misclassification rate by comparing the misclassification rate of the best tree with the misclassification rate of the null model (De’ath & Fabricius 2000), and by using cross-validated samples (Steinberg & Colla 1995) as specificity (i.e. the ability of the model to predict that a species is not eradicated when it is not) and sensitivity (the ability of the model to predict that a species is eradicated when it is) (Bourg et al., 2005).

The optimal trees were represented graphically, with the root standing for the undivided dataset at the top, and the terminal nodes, describing the most homogeneous groups of data, at the bottom of the hierarchy. The quality of each split was expressed by its improvement value, corresponding to the proportion of the overall misclassification rate explained by the split, with high scores of improvement values corresponding to splits of high quality. Surrogates of each split, describing the splitting rules that closely mimicked the action of the primary split, were assessed and ranked according to their association values, with the highest possible value 1.0 corresponding to the surrogate producing exactly the same split as the primary split. Because it is easier to be a good splitter on a small number of records, missing explanatory variables have an advantage as splitters. To circumvent this problem, the explanatory variables were penalized in proportion to the degree to which they were missing and treated by back-up rules, based on the surrogates specific to each split, that closely mimicked the action of the primary splitters. To reduce the splitting power of high categorical explanatory variables, these were also adjusted to have no inherent advantage over continuous explanatory variables, following penalization rules set out by Steinberg & Colla (1995) .

Results

Worldwide data - overview

Data pertaining to 171 eradication campaigns against 102 different species were assembled by July 2009. Appendix 2 gives an overview of the database and Table 2 shows the campaigns divided into 7 pest groups (bacteria, fungi, insects, nematodes, phytoplasma, plants and viruses/virus-like organisms) and continents.

Affected systems

Of the 171 campaigns, 82 were directed against an organism that was regarded as an agricultural pest, 44 that were targeted against organisms considered a problem in forestry, 50 where the pest was a problem for ornamental plants, and 83 against organisms that harm natural ecosystems. See Table 3 for an overview. Most interventions were performed in outdoor systems (134 campaigns), only 22 campaigns were explicitly performed in protected systems, such as glass- or shade-houses, and 15 campaigns addressed a pest problem in both protected and outdoor systems.

Aims of campaigns

The vast majority of the campaigns (126, against 81 species) were designed for eradicating the pest organism and will be further analysed and discussed. The remaining 45 campaigns aimed at eradicating, containing or suppressing the pest, depending on the situation in an area. However, the focus of the review was on eradication campaigns, it is therefore likely that the assembly of campaigns not explicitly aimed at eradicating a pest is not complete and that many more containment and suppression campaigns exist.

European data: aim and success

The 87 European campaigns were directed against 74 species and 64 of these campaigns were designed for eradications (Table 4). Out of these 64 European eradication campaigns, 41% were successful, 22% are likely to be successful, whereas 21% are likely to fail or failed altogether (16%). Of the 64 eradication campaigns, 26 are still ongoing (see appendix 2).

Outside Europe: aim and success

Outside Europe, 86 campaigns directed against 61 species were collated. Sixty-two of them aimed at eradicating the pest organism (Table 4). Similar to the European eradication campaigns, the majority of these campaigns were successful (45%) or likely to succeed (18%), whereas 31% are likely to fail or failed altogether (6%). There was no significant difference in the outcomes between European and non-European eradication campaigns ($p = 0.26$, Table 4).

Dataset analysed

Of the 126 eradication campaigns collected worldwide and analysed here, 44% were successful (level 3), 20% were likely to be successful (level 2), whereas 25% were unlikely to succeed (level 1) and only 11% of the campaigns were clear failures (level 0). About one third (41 cases) of the eradication campaigns were implemented on islands, the remaining 85 were implemented on the mainland. The duration of the campaigns varied widely and ranged from less than a month up to 384 months (or 32 years), see Figure 1. The time elapsing between the arrival of an organism and the beginning of management measures ranged from 0.5 to 105 years and this measure was used for the LME analysis. For CART, this measure was converted into months and two additional time variables were calculated (see Appendix 3 for details). A wide range of control measures were applied and often in varying combinations. Most widely used were chemical (including spraying by *Bacillus thuringiensis* and pheromone traps, N=87) and physical measures (uprooting, burning, chipping and other disposal methods of plant material, N=87), followed by cultural (changed crop rotation, planting of resistant hosts, N=20), sanitary (movement of possibly infested plant material or equipment prohibited, N=19) and biocontrol measures (include Sterile Insect Techniques, N=18). As for introduction pathways, most often (N=61) the infestation could be retraced to contaminated goods (e.g. plant material), followed by natural spread from an already infested area (N=29), hitchhikers (tyres, luggage, ballast water, no specific commodity, N=15) and introductions along a corridor (introduced via transport infrastructure, N=11). Only 4 introductions had reportedly escaped from captivity.

LME analysis

The best model shown in Table 5 included the factors related to open or closed systems, the level of knowledge and readiness to act as well as the group "pathogens". Eradications in closed systems ($p = 0.018$), and a high readiness to act were significantly related to successful campaigns ($p = 0.032$). Furthermore, pathogens were significantly more difficult to eradicate than insects ($p = 0.040$). The group "plants", continentality and the level of coordination remained in the best fitting model but had no significant effect. The factors related to spatial scale and quick reaction were not significant and were thus excluded from the model.

CART analysis

The prediction model for eradication success had a low misclassification rate (number of cases of their total number that were classified in the wrong group) and a high value of sensitivity (see Figure 3 for the model and Appendices 4 and 5 for a full summary and diagnostic information). The overall misclassification rate of the optimal tree is 15.4%, compared to 50% for the null model. The sensitivity of the model (its ability to predict that a species is eradicated when it actually is) is 0.739; the specificity of the model (its ability to predict that a species is not eradicated when it is not) is 0.571. Low eradication success in inaccessible areas appeared to be the strongest predictor (see Terminal node 6 in Figure 3). For most cases (94), the accessibility of the infested sites was considered unproblematic, while in 10 cases, some accessibility constraints were reported. For 17 campaigns, accessibility was a problem either because the access to private properties was not possible or because remote areas were concerned. For accessible areas, the eradication was more difficult for fungi and related organisms (including the phyla Ascomycota, Basidiomycota, Oomycota but also Tenericutes, the phylum of phytoplasma) and nematodes (Terminal node 5) than for insects, plants, bacteria and viruses. Information about the phyla for viruses was lacking in the dataset, hence was treated as missing values. However, they were grouped together with insects, plants and bacteria, when surrogates were used. For this latter group, the probability of success was higher for smaller (up to approx. 4,000 ha) than larger infested areas (above approx. 4,000 ha). The size of the infested area was biased towards small size infestations; for 46 campaigns, the area was below 4,000 ha, 17 cases ranged between 4,000 and 40,000 ha and 13 campaigns were encompassing more than 40,000 ha (Figure 3). In small infested areas, the eradication success was strongly decreasing when the species naturally spread from an already infested area (Terminal node 2 compared to 1). This mode of unaided introduction was reported from 29 campaigns. In large infested areas, the ease of pest detection and its identification decreased the probability of successful eradication (Terminal node 4 comparing to 3). The ease of detection and identification of a species was considered at three levels: “easy” (N=72) if the organism was identifiable with the naked eye; “intermediate” (N=29) if a microscope and literature were needed for the identification and “difficult” (N=24) if more complex tools/molecular tools were needed to identify the species.

Discussion

General overview of eradication database

The vast majority of invertebrate and pathogen campaigns concern pests of agriculture, forestry or ornamental plants. Plant pests are eradicated mainly for socioeconomic rather than for conservation reasons, unlike many vertebrate and plant eradication campaigns (Genovesi, 2005). Although most of the invertebrate and pathogens were also considered to present a potential ecological problem, no record in the database states ecological threat as an exclusive reason for conducting a campaign. Our review suggests that only invasive alien plants were eradicated for exclusively ecological reasons. A possible explanation for this is that long-term chemical control strategies are not considered a viable option to control invasive plants in nature reserves or recreational areas such as riverbanks. This may provoke weed managers to choose other more environmentally friendly eradication measures for conservation purposes in such areas.

In the agricultural sector, there were examples of eradication campaigns against all groups of pests (bacteria, fungi, insects, nematodes, phytoplasma, weeds and viruses), probably because this sector includes a wide range of perennial and annual host plants. Our review also suggests that (with the exception of fungi) pathogens were not attempted for eradications in the forestry sector and for ecological reasons. While the finding is surprising for forestry, it may well be that ecological impacts due to viruses and bacteria are perceived as much less of an issue (see also lack of ecological impact assessment for these taxonomic groups in task 2-2) and even fewer eradication measures were taken against them. But it may well be that forest pathogens are usually detected so late that eradication measures are not a valuable management option anymore.

Hypotheses (LMEs)

i) Our expectation that small-scale eradications would be more successful than large-scale campaigns is not supported by the analyzed data. However, this finding might be biased: thorough monitoring of large areas is more difficult and some escapees might have been easily overlooked (Rout *et al.*, 2009). This could have led to a more optimistic declaration of eradication success. Conversely, small scale infestations may well turn out to be more widespread than thought in the beginning, thus leading to the conclusion that the campaign failed or is likely to fail. On the other hand, large-scale and especially international campaigns are usually better organised and conducted than smaller outbreaks (Grefenstette *et al.*, 2008). Before bilateral campaigns are started, the area of infestation, legal responsibilities, biological information of the pest organism and adequate management measures are the subject of an intensive evaluation process and in some cases, cost-benefit analysis, see for example eradication plans against the pink bollworm *Pectinophora gossypiella* or the boll weevil *Anthonomus grandis* in the United States (El-Lissy & Grefenstette, 2007, Grefenstette *et al.*, 2008). Usually for international campaigns, a specific campaign or program is launched that also addresses public education and risk communication. Only if, on the basis of these prior considerations, success seems likely, will they be started. All in all, international programs, by definition, are probably less of an *ad hoc* endeavour. It should be noted however, that the CART analysis included hectares as size measure and this turned out to be an important factor in our dataset (see paragraph on CART analysis)

ii) The hypothesis that island eradications are more successful than mainland campaigns is not supported by the analysis of our data. An explanation could be that other factors are important for plant pests than for vertebrate eradications, from where the assumption was drawn (Clout & Veitch, 2002, Krajick, 2005). Most plant pests are unintentional introductions which correlate with the volume of traded goods (especially plant materials) and travel volume (Hulme *et al.*, 2008). Therefore, the insularity of an area does not seem to be relevant for the occurrence of a plant pest and the outcome of management measures taken against it. Islands are perhaps, more aware of the problem of invasive species and thus have better systems to prevent unwanted introductions (Stokes *et al.*, 2006). Just like mainland countries, island authorities are continually improving their surveillance and early detection schemes to improve the protection of their vulnerable ecosystem (Wilson *et al.*, 2004, Criticos *et al.*, 2005).

Our expectation, that closed system eradications would be more likely to succeed, was confirmed by the data. Apparently, the more complex and open the target area is, the more unlikely is the success. It might therefore be a reasonable strategy to aim at eradication in closed systems and to contain the same species where it occurs in outdoor systems below damage level. The reliance of the organism on the particular environment created by the closed system (e.g. in a glasshouse) may also make it more vulnerable to control measures that target all life stages within that system.

iii) It is widely argued in the literature, that early detection and rapid action are favourable for a successful eradication (Simberloff, 2003). We tested the time elapsed between the detection of a pest and the start of management measures and we found no significant influence of rapid action on the outcome of a campaign. While this finding is surprising, it should be noted that our tested variable may not be a strict measure of early detection. Because the real arrival time (or date) of an organism is often not known with certainty, a reliable estimation of the time elapsed between the arrival of an organism and the beginning of the campaign was not possible in many cases, and this made the test for the significance of early detection difficult. However, it should be noted that in practice, the first detection is the only indication available of the time of arrival of a pest organism. In practice, there may be circumstantial evidence indicating an earlier arrival date, but this is often anecdotal or remains unrecorded.

iv) Our analysis revealed that extensive preparation for eradication might pay if a high-risk organism is found. Eradications are drastic measures and often imply ecological and social ramifications, opposition from the public can be expected in many cases and is often inevitable, and stakeholder groups have differing interests (Bremner & Park, 2007). However, proactive phytosanitary authorities may be able to circumvent such obstacles to a certain degree if they prepare reaction scenarios for themselves and stakeholder groups before an outbreak occurs. The public is often highly supportive of eradication campaigns if the risks and benefits are clearly communicated (Bremner & Park, 2007, Hosking *et al*., 2003). Therefore it is advisable for a country or a larger entity to develop strategies, or contingencies for reacting to high-risk plant pests. As suggested elsewhere (Wittenberg & Cock, 2001), national and regional plant protection organisations should (and often do) invest in the development of contingency plans and establishment of PRAs. It is somewhat surprising that an analysis of the ‘degree of cooperation’ failed to be significantly linked with a successful eradication campaign. However, this variable was derived from the questionnaire and might be too suggestive (90 out of 126 replies considered the coordination to be strong, only one respondent admitted that cooperation was lacking), unlike the question whether contingency plans were available prior to the outbreak. Hence, the appropriateness of this variable to test for the importance of cooperation can be criticized. However, this problematic highlights the difficulties in reliably testing such “soft” factors in a large-scale survey such as ours.

Overall, it may be true that a “quick-and-dirty” reaction as propagated by Simberloff (2003) is crucial for eradicating conspicuous IAS, especially vertebrates, but for eradicating plant pests, more sophisticated planning and perhaps even the application of more costly long-term eradication measures seem more promising (Henneberry, 2007). In the case of plant pest eradications, which mainly take place in agricultural settings, the drivers for initiating a campaign might be different from those in conservation programmes, that have been reviewed up to now (Genovesi, 2005, Simberloff, 2009). Therefore, other factors than previously thought might be relevant for a successful outcome of plant pest eradications. Successful eradication of forest pests from urban areas (e.g. Hosking *et al*., 2003), suggest that the support of the local population is very important, particularly where potentially unpopular measures, such as aerial application of insecticides, are involved. Efforts to manage invasive pests may also be limited by the lack of cost-effective technologies for eradicating them and research and development of effective control methods are often needed. The US Government Accountability Office evaluated the federal response to three major invasive forest pests in the USA—the Asian longhorned beetle (*Anoplophora glabripennis*), the emerald ash borer (*Agrilus planipennis*) and *Phytophthora ramorum* (the pathogen that causes Sudden Oak Death) — and concluded that efforts to eradicate them were limited by the lack of available cost-effective technologies (GOA, 2006).

It can also be argued, that many other factors are relevant – or thought to be relevant – for the successful outcome of a campaign; that is also a reason, why our questionnaire is so extensive and why we used the novel approach with CART analysis.

What we can say with confidence from the LME analysis, is that 1) ‘indoor’ eradications have good chances to succeed and 2) that having a thorough strategy (or plan) in place for how to react to the arrival of a new plant pest, pays off in terms of eradication success. While it is advisable to react quickly to interceptions and outbreaks of high-risk organism, a short reaction time will not by itself guarantee success, and needs to be linked to a good and detailed strategy on how to act after an incursion.

CART analysis

This analysis was applied to 'mine' our extensive eradication database for meaningful factors related to successful eradication campaigns, without *a priori* formulated hypotheses. CART enabled us to discover generalities that might otherwise have been omitted (or overlooked) if we had focused only on hypothesis testing.

The most important factor for the success of an eradication campaign proved to be the accessibility of the infested area. In our dataset, most campaigns with accessibility problems were not successful. This explanatory variable contains two notions: first, it may be that the infested area was in a remote area and thus physically difficult to access, and second, it may be that legal constraints prevented the pest managers from entering infested private properties. While there is no real scope to improve the access to remote areas, the second problem can be addressed by NPPOs. When designing contingency plans for a quarantine organism, it will be important for NPPOs to address the issue and create the legal framework that allows pest managers to enter private properties and carry out necessary control measures during an eradication campaign.

Within the campaigns in easily accessible areas, those addressing fungi and nematodes were less successful than those against insects, plants and bacteria. This may be an indication that fungi, and fungi-related organisms, share biological properties, enabling them to better withstand eradication measures than insects, plants and bacteria. It can be argued that fungi share many traits with bacteria and viruses and we thus included the explanatory variable micro-organism vs. macro-organism into the analysis. However, this variable was not important. The difficulties to eradicate fungi suggest strategies other than eradication would be more appropriate to control the damage of this group of plant pests. It can thus be argued that it is best to invest in containment or suppression measures, if a phyto-pathogenic fungus is found. However, more analysis may be needed before recommendations for practice are implemented and this could be part of task 5.3 in PRATIQUE.

Within the group of insects, plants and bacteria, infested areas that were smaller than approx. 4,000 ha were more likely to be successfully disinfested than larger areas. This supports previous analysis showing that successful eradication of invasive plants is unlikely if the infested area exceeds 1,000 ha (Rejmánek & Pitcairn, 2002). Our finding shows the importance of a good surveillance system: if an organism is found soon after its arrival, the infested area will still be relatively small and eradication is more feasible. This point needs even more attention because our analysis also suggests that spreading abilities of the harmful organism are crucial for the outcome of a campaign. It appears that organisms that spread naturally from an already infested area are more difficult to eradicate, also because they will be able to enlarge the infested area, probably beyond the threshold of approx. 4,000 ha suggested to be crucial for success in our analysis. The importance of the size of the infested area calls for efforts to be focussed on early detection an infestation. And in the case of an incursion, it will be important to delimit the area of infestation prior to deciding whether eradication is an achievable goal or whether other phytosanitary measures are more appropriate.

The negative effect of detectability on the probability of eradication of large outbreaks is counterintuitive at first sight. However, it may well be that inconspicuous organisms are more easily overlooked in surveys, especially in large scale outbreaks, and this could lead to a premature declaration of success while the organism is still present (Rout et al., 2009). For conspicuous, easily identifiable organisms, such as plants, erroneous declaration of success is less likely because it is obvious that the organism is still present. Another possible explanation is that invasions that are difficult to detect may not be as advanced as those that are easily detectable and therefore more likely to be eradicated.

Applicability of the solidarity dossiers

It is apparent from Table 2 in Appendix 1, that despite our best efforts, the 'coverage' of the eradication and containment campaigns in the EU, in terms of these solidarity claims, is somewhat patchy and is by no means representative of all of the plant health eradication and containment campaigns being implemented in EU MSs. This is partly because only campaigns totalling more than EUR 50,000 per year are claimed for, but also because many of the campaigns are on-going and cannot be considered as discrete eradication events. In many countries the pest is still present, sometimes under control, sometimes spreading (see Table 1 in Appendix 1). However, the data was useful in 1) providing estimates for the costs of some of the campaigns (N = 3) in the PRATIQUE task 5.1, review and analysis of eradication campaigns; and 2) providing information on certain campaigns which had not previously been captured or known about (N = 18). Some of these may be of little or no value to the analysis of eradication events (e.g. the *Diabrotica v. virgifera* outbreak front moving across Poland and Austria) as they are just a 'snapshot' in time and space (i.e. of a pest in a limited part of its outbreak range and for only one year). There are also many cases where we have an example of the eradication of a pest elsewhere in the EU but we do not have it for a particular MS (*Diabrotica v. virgifera* in Belgium; *Erwinia amylovora* in Austria, France and Spain). Finally, there are a few examples of smaller, or localized campaigns against pest species which were not captured at all in the eradication database (see species names in bold in Table 2 in Appendix 1). Many of these are probably not completed eradication campaigns or concern yearly eradications of outbreaks in restricted glasshouse situations (*Potato spindle tuber viroid*, *Bemisia tabaci* and *Liriomyza* spp.). However, representative examples of these type of limited (within glasshouse) eradication campaigns were included in the analysis (e.g. for *B. tabaci*, *T. palmi* and *L. trifolii*). N.B. not all EC countries are represented in PRATIQUE although an attempt has been made to cover the EU as completely as possible.

One of the main limitations of the Solidarity data, in terms of the PRATIQUE project, apart from the fact that not all of the costs of eradication and containment may be contained within a claim, is that the claims are only for one calendar year. In many cases, with pests such as *Diabrotica v. virgifera*, *Anoplophora spp*. and others (see Table 1 in Appendix 1) the campaigns are on-going and the overall costs (and outcomes) of the campaign cannot be determined. In other cases, such as with *D. v. virgifera*, claims refer only to the measures taken with respect to the pest spreading across a MS (e.g. Poland), but these are not discrete eradication events; the pest is expanding across a large front moving north and east across Europe. Pinewood nematode is another example of a large outbreak, which appears to be spreading. Thus, costs associated with one particular year in one particular region of an outbreak probably have little bearing on the overall costs associated with a large outbreak. Nonetheless, campaigns are managed at the country level and we thus considered costs per country, and summed the costs per country and harmful organism for analyses. Nevertheless, the Solidarity data does provide a picture of the complexities of eradication campaigns, and illustrates the fact that they are often trans-national and long-lived. Coming to conclusions on the time and money spent on such large campaigns is not trivial, and needs to be collated at a EU level, similar to campaigns from the USA, Canada or Australia, that include several states or provinces. Another, similar problem, with interpreting Solidarity claims in terms of expenditure on eradication or containment campaigns is that there is a threshold (currently

EUR 50 000), below which claims cannot be made. Thus, on-going monitoring costs may not be captured in this way.

Hence, even though the search on the CIRCA server revealed new cases for the eradication database with plentiful of information about them, not all of these cases proved to be useful for our analyses. They could however be added to the eradication database for completeness if this database shall be made public.

Recommendations for practice

Our eradication database is unique in its nature, since no-one has ever attempted to collate and analyse eradication campaigns of plant pests worldwide. Such a compilation will be of interest to other researchers, and it will also be a useful resource for plant pest managers to consult. While some information is of a confidential nature, it could nevertheless be made public if appropriately edited (i.e. such that it contains no information which is not in the public domain).

The statistical analysis of the eradication database of plant pests only partly confirmed some of the general assumptions made in the literature about relevant factors for eradication success. It did however, confirm 1) that eradication campaigns are more likely to succeed in closed systems and 2) that readiness to act swiftly, positively affects the outcome of a campaign. The CART analysis included more factors than the LMEs analysis and highlighted the importance of the size of the infested area, including whether it can be easily accessed. Accessibility is therefore a key factor, although the reasons why the infested areas were difficult to access could be related to remoteness or simply the absence of legal powers to enter private properties. It also showed that particular care needs to be taken if the organism is a fungal pathogen as these appear to be either more resilient to eradication methods, or for other reasons are less likely to be eradicated than other taxa. Our CART analysis suggests that all of these factors will need to be taken into account when designing a contingency plan against quarantine plant pests. Some of the more counterintuitive findings also deserve close attention. For example, the negative relationship between detectability and the probability of successful eradication suggests an alternative hypothesis: that difficult to detect (i.e. small and inconspicuous) invaders may not in general become as well established as those that are easily detectable. Alternative hypotheses suggested by the outcome of this initial analysis could be further investigated and tested using the existing database, but also serve as guides to focus future research on this topic. What is certain is that not all of the general assumptions and hypotheses relating to eradication success were supported by our analyses. Whilst some of these findings may have been related to the design and limitations of this particular study, albeit the first attempt to do this worldwide, they also support the assertion that factors influencing both invasion and eradication success are complex and not yet fully understood. We propose evaluating the usefulness of these factors for a generic decision support scheme in task 5.3 of the PRATIQUE project.

Literature

Baker RHA, Battisti A, Bremmer J, Kenis M, Mumford J, Petter F, Schrader G, Bacher S, De Barro P, Hulme PE, Karadjova O, Lansink AO, Pruvost O, Pysek P, Roques A, Baranchikov Y & Sun JH (2009) PRATIQUE: a research project to enhance pest risk analysis techniques in the European Union. *EPPO/OEPP Bulletin* **39**, 87-93.

Bartlett PW (1979) Preventing the establishment of Colorado beetle in England and Wales. In *Plant health (eds Ebbels DL & King JE)*. Blackwell Scientific Publications, Oxford.

Baxter PWJ, Sabo JL, Wilcox C, McCarthy MA & Possingham HP (2008) Cost-Effective Suppression and Eradication of Invasive Predators. *Conservation Biology* **22**, 89-98.

Bourg NA, McShea WJ & Gill DE (2005) Putting a cart before the search: Successful habitat prediction for a rare forest herb. *Ecology* **86**, 2793-2804.

Breiman L, Friedman JH, Olshen RA & Stone CJ (1984) *Classification and regression trees*. Wadsworth International Group, Belmont, California, USA.

Bremner A & Park K (2007) Public attitudes to the management of invasive non-native species in Scotland. *Biological Conservation* **139**, 306-314.

Cannon RJC, Matthews L, Collins DW, Agallou E, Bartlett PW, Walters KFA, Macleod A, Slawson DD & Gaunt A (2007) Eradication of an invasive alien pest, Thrips palmi. *Crop Protection* **26**, 1303-1314.

Carey JR (1996) The incipient Mediterranean fruit fly population in California implications for invasion biology? *Ecology* **77**, 1690-1697.

Clout MN & Veitch CR (2002) *Turning the tide of biological invasion: the potential for eradicating invasive species*. IUCN, Gland.

Criticos DJ, Phillips CB & Suckling DM (2005) Improving border biosecurity: potential economic benefits to New Zealand. *New Zealand Plant Protection* **58**, 1-6.

De'ath G & Fabricius KE (2000) Classification and regression trees: a powerful yet simple technique for ecological data analysis. *Ecology* **81**, 3178-3192.

EC (2000) Council Directive 2000/29/EC of 8 May 2000 on protective measures against the introduction into the Community of organisms harmful to plants or plant products and against their spread within the Community.

EC (2003) Commission Decision of 24 October 2003, on emergency measures to prevent the spread within the Community of Diabrotica virgifera Le Conte. Council directive 2003/766/EC. .

El-Lissy O & Grefenstette B (2007) Progress of Boll Weevil Anthonomus grandis Eradication in the United States of America, 2005. In *Area-wide Control of Insect Pests from Research to Field Implementation*, pp. 547-558.

EPPO (2009) PM 9/10: Generic elements for contingency plans.

FAO (1998) Guidelines for pest eradication programmes (ISPM 6). In *International Standards for Phytosanitary Measures*, Rome.

Garcia-Llorente M, Martin-Lopez B, Gonzalez JA, Alcorlo P & Montes C (2008) Social perceptions of the impacts and benefits of invasive alien species: Implications for management. *Biological Conservation* **141**, 2969-2983.

Genovesi P (2005) Eradications of invasive alien species in Europe: a review. *Biological Invasions* **7**, 127-133.

Genovesi P (2007) Limits and Potentialities of Eradication as a Tool for Addressing Biological Invasions. In *Biological invasions, ecological studies 193*, pp. 385-402. Springer-Verlag, Berlin Heidelberg.

Grefenstette W, El-Lissy O & Staten RT (2008) Pink bollworm eradication plan in the US, Updated February, 2008. *United States Department of Agriculture, Animal and Plant Health Inspection Service, Riverdale, MD/Phoenix, AZ.*

Henneberry TJ (2007) Integrated Systems for Control of the Pink Bollworm Pectinophora gossypiella in Cotton. In *Area-Wide Control of Insect Pests*, pp. 567-579.

Hulme PE, Bacher S, Kenis M, Klotz S, Kuhn I, Minchin D, Nentwig W, Olenin S, Panov V, Pergl J, Pysek P, Roques A, Sol D, Solarz W & Vila M (2008) Grasping at the routes of biological invasions: a framework for integrating pathways into policy. *Journal of Applied Ecology* **45**, 403-414.

Krajick K (2005) Ecology - Winning the war against island invaders. *Science* **310**, 1410-1413.

Liebhold A & Bascompte J (2003) The Allee effect, stochastic dynamics and the eradication of alien species. *Ecology Letters* **6**, 133-140.

Mack RN & Lonsdale WM (2002) Eradicating invasive plants – hard-won lessons from islands. In *Turning the tide: the eradication of invasive species*. IUCN SSC Invasive Species Specialist Group, Gland, Switzerland and Cambridge, UK.

Myers JH, Savoie A & Randen E (1998) ERADICATION AND PEST MANAGEMENT. *Annual Reviews in Entomology* **43**, 471-491.

Myers JH, Simberloff D, Kuris AM & Carey JR (2000) Eradication revisited: dealing with exotic species. *Trends in Ecology & Evolution* **15**, 316-320.

Olson LJ & Roy S (2002) The economics of controlling a stochastic biological invasion. In *Annual Meeting of the American-Agricultural-Economics-Association (AAEA)*, pp. 1311-1316. Blackwell Publishers, Long Beach, California.

Rejmánek M & Pitcairn MJ (2002) When is eradication of exotic pest plants a realistic goal? In *Turning the tide: the eradication of invasive species*. IUCN SSC Invasive Species Specialist Group, Gland, Switzerland and Cambridge, UK.

Rout TM, Salomon Y & McCarthy MA (2009) Using sighting records to declare eradication of an invasive species. *Journal of Applied Ecology* **46**, 110-117.

Rout TM, Thompson CJ & McCarthy MA (2009) Robust decisions for declaring eradication of invasive species. *Journal of Applied Ecology* **46**, 782-786.

Simberloff D (2003) Eradication-preventing invasions at the outset. *Weed Science* **51**, 247-253.

Simberloff D (2003) How Much Information on Population Biology Is Needed to Manage Introduced Species? *Conservation Biology* **17**, 83-92.

Simberloff D (2008) We can stop the invasion juggernaut! - High- and low-tech success stories. *Neobiota* **7**, 5-18.

Simberloff D (2009) We can eliminate invasions or live with them. Successful management projects. *Biological Invasions* **11**, 149-157.

Steinberg D & Colla P (1995) *CART: Tree-structured non-parametric data analysis*. Salford Systems, San Diego, USA.

Stokes KE, O'Neill KP, Montgomery WI, Dick JTA, Maggs CA & McDonald RA (2006) The importance of stakeholder engagement in invasive species management: A cross-jurisdictional perspective in Ireland. *Biodiversity and Conservation* **15**, 2829-2852.

Touza J, Dehnen-Schmutz K & Jones G (2007) Economic Analysis of Invasive Species Policies. In *Biological invasions, ecological studies 193*, pp. 354-366. Springer-Verlag, Berlin Heidelberg.

Vreysen MJB (2007) *Area-Wide Control of Insect Pests*.

Wilson JA, Stephenson BP, Gill GSC, Randall JL & Vieglais CMC (2004) Principles of response to detections of new plant pest species and the effectiveness of surveillance. *New Zealand Plant Protection* **57**, 156-160.

Wittenberg R & Cock MJW (2001) *Invasive alien species: a toolkit of best prevention and management practices*, CAB International edn, Wallingford (GB).

Tables and Figures

Table 1: Detailed questionnaire for eradication database

Question Nbr.	Topic	Question	possible answer
1	**Identification of event**	**Which species was controlled where and when?**	**English name, country, region, year**
2		To which pest group does the pest organism belong to?	choose from a) insect, b) mite, c) nematode d) bacteria e) fungi f) virus or virus-like g) plant
3		To which genus does organism belong to?	latin name
4		What is the species name of the organism ? (latin name)	free text
5		Continent where management measures were performed	free text
6		Country where management measures were performed	free text
7	Location of management measures	Target area where management measures was performed (county, region, etc)	free text
8	Description of damage	Direct impact on plants	free text
9	Description of damage	Indirect impacts to animals, ecosystem changes, economic damages, problems for human/animal health	free text
10	Invaded habitat type	EUNIS category A: marine habitats	yes - no
11		EUNIS category B: coastal habitats	yes - no
12		EUNIS category C: inland surface waters	yes - no
13		EUNIS category D: mires, bogs and fens	yes - no
14		EUNIS category E: grasslands, and lands dominated by forbs, mosses or lichens	yes - no
15		EUNIS category F: heathland, scrub and tundra	yes - no
16		EUNIS category G: woodland, forest and wooded land	yes - no
17		EUNIS category H: inland unvegetated or sparsely vegetated habitats	yes - no
18		EUNIS category I: regularly or recently cultivated agricultural, horticultural and domestic habitats	yes - no
19		EUNIS category J: constructed, industrial and other artificial habitats	yes - no
20	Location of management measures	Targeted system:	choose from a)protected (glasshouse) b) outdoors, cultivated c) outdoors, noncultivated, private d)outdoors, noncultivated, public
21		If measures are taken in an outdoor system, please indicate within which altitudinal range (meters	(meters above sea level)

		above sea level)	
22	Spatial extent of the pest outbreak	Number of infested lots, consignments, glasshouses, fields, gardens, park areas, etc.	continuous
23		Size of infested area in km2, ha or m2	continuous
24		What proportion of suitable habitat is infested at the onset of the measures?	%
25	Properties of the event	Is infested area difficult to access for management measures (such as private gardens, homes, remote areas?)	yes - no
26	Objective of management strategy	What management strategy was chosen?	choose a) eradication b) containment
27	Management measures	What management measures were taken? a) physical b) chemical c) biocontrol agents d) combined e) others (brief description, see sheet "measures" for possible answers)	choose from a) physical b) chemical c) biocontrol agents d) combined e) others (brief description, see sheet "measures" for possible answers)
28		Were management measures/techniques available at moment of outbreak? If yes, were they ever successfully applied for this organism?	yes - no
29		What kind of information was available concerning management measures for this organism prior to its arrival?	choose from a) a PRA b) a species specific contingency plan c) a generic contingency plan d) other sources (e.g. a pest notice or alert), please specify briefly e) none (or had to be compiled during the outbreak)
30	Properties of target population	Population size when measures are taken (individuals)	continuous
31		Population density (individuals per area); please choose magnitude of area as seems appropriate for the organism	ratio
32		Population trend before management measures were taken: expanding, stable, decreasing	scores
33		Was the population reproducing in the infested area?	yes - no
34		Distribution of pest populations in infested area	choose from a) patchy (i.e. reproductively isolated populations) vs. b) continuous
35		Are interactions with other aliens known? if yes, what are they?	free text
36	Introduction	Pathways of original introduction:	choose from a) intentional release, b) escape from captivity, c) contaminant of goods (e.g. plant material) d) hitchhiker e) corridor (introduced via transport infrastructure), f) unaided (natural spread from an already infested area
37		Rate of introduction:	choose from a) none b) once in 10 years or less c) once a year d) several

			times a year
38		Pathways in ongoing introduction:	choose from a) intentional release, b) escape from captivity, c) contaminant of goods (e.g. plant material) d) hitchhiker e) corridor (introduced via transport infrastructure), f) unaided (natural spread from an already infested area
39	Preventive measures	Are measures taken to prevent introductions? If yes, what are they (list of possible measures see sheet "measures")	free text
40	Monitoring	Is the population monitored while the eradication/containment campaign is underway? How?	free text
41		Are initial infection sources retraced (at time of detection)?	yes - no
42	Detection	How was pest detected?	choose a) inspection at import b) inspection at nursery c) grower, d) public e) regular NPPO survey
43		Ease of detection and identification:	choose a) identifiable with naked eye, b) microscope and literature needed for identification, c) more complex tools (molecular) needed to identify species
44	Timing	Arrival date (if known, else first record)	DD.MM.YYYY
45		Date of 1st record of spreading	DD.MM.YYYY
46		Date when impact was recognised	DD.MM.YYYY
47		Date when impact was considered a problem	DD.MM.YYYY
48		Date when evaluation process started	DD.MM.YYYY
49		Date management measures started	DD.MM.YYYY
50		Date management measures ended or will end	DD.MM.YYYY
51	Legal and Organisational Constraints	What is pest status of organism?	choose from a) quarantine pest b) regulated non-quarantine pest c) neither
52		What strategies to manage invasive alien species exist?	free text
53		Level of coordination between involved parties:	choose from a) none b) existing c) well functioning
54	Human dimension	Degree of public support for management measures:	choose from a) opposed b) indifferent c) supporting
55		Degree of stakeholder commitment for management measures:	choose from a) opposed b) indifferent c) supporting
56		Was the issue of [risk] communication to the public and/or other stakeholders specifically addressed?	yes - no

57	Effort put in management measures	How much money was spent on eradication? If available, give absolute values, or alternatively, estimate costs where possible, IMPORTANT: state if costs are estimates!	monetary values or estimates based on following categories: a) < € 10,000; b) €10,000–50,000; c) €50,000–£500,000; d) €500,000 – €5,000,000; e) > €5,000,000; f) unknown or estimation not possible.
58		How much labour was involved in the campaign? Paid workers or unpaid volunteers. E.g. was the public asked to participate in the removal of pest?	free text
59		How adequate was the effort put in the campaign?	choose from a) less than adequate for the extent of the outbreak b) adequate c) more than adequate
60	Level of success of management measures	Level of control/pest management, achieved in the attempted time frame:	choose from a) organism eradicated, campaign ended; b) organism contained or delimited, campaign continues/d; c) organism suppressed, campaign continues d) alternative measures to be applied; e) all measures failed, pest established.
61		If stated or considered, how was the success or failure of the campaign determined?	choose from a) monitoring (please indicate on what basis and how long) b)expert judgement c) other method, please explain
62		Were any suggestions or conclusions provided regarding reasons for the success/failure of the campaign?	free text
63	History of the pest species	Did pest occur elsewhere in the world? If yes, please say where (country, region, etc)	free text
64		If pest occurred elsewhere, where measures taken against it?	yes - no
65		If management measures were taken elsewhere in world, what were they:	choose from a) physical b) chemical c) biocontrol agents d) combined e) others (brief description)
66		If management measures were taken elsewhere in world, what was their outcome?	free text
67	Remarks	Do you have comments? Please specify which question they relate to.	free text
68	References	Where are information about event-specific factors from? Specify which source contributes which information.	free text
69	DataEntry	Name, institution and country of person entering the data	
70		Date of data entry	

Table 2: Number of eradication and containment campaigns in the eradication database, separated by continent and pest group.

	Pest group							
Continent	bacteria	fungi	insect	nematode	phytoplasma	plant	virus(like)	Total
Africa						2		2
Atlantic			1					1
Asia								0
Australia/NewZealand	1	1	8			13		23
Europe	10	16	42	2	1	7	9	87
IndianOcean			1					1
NorthAmerica	2	3	20	1		10	1	37
Pacific			2	1		10		13
SouthAmerica	1		6					7
total	14	20	80	4	1	42	10	171

Table 3: Affected systems and pest groups. An organism can be included in more than one system.

Pest Group	agriculture	ecology	forestry	ornamental
bacteria	11			3
fungi	9	7	12	10
insect	48	34	30	34
nematode	2	2	2	2
phytoplasma	1			
plant	2	40		
virus(like)	9			1
total	82	83	44	50

Table 4: Comparison between European and non-European eradication campaigns. The level of success does not differ between the two groups (Chi2 = 4.04, df = 3, p = 0.26).

Level of success	EU	nonEU	total
successful	27	28	55
expected success	14	11	25
expected failure	13	19	32
failure	10	4	14
total	64	62	126

Table 5: Relationship between the outcome of eradication campaigns and factors standing for i) the spatial extent of the infestation, ii) continentality and open or closed system campaigns, iii) the reaction time between arrival and start of management measures and iv) the level of readiness and coordination. The best fitting model is shown, delta AIC 3.7659 (with previous model) and 12.1571 (with next model)

Factors in multivariate analysis	Estimate	Std. Error	DF	t-value	p-value
Intercept	2.927	0.789	43.000	3.712	**0.001**
Open or closed systems	-0.460	0.184	31.000	-2.505	**0.018**
Readiness to act	0.258	0.115	31.000	2.240	**0.032**
Pestgroup pathogen	-0.625	0.295	43.000	-2.115	**0.040**
Pestgroup plant	0.628	0.390	43.000	1.611	0.115
Continentality	-0.222	0.258	31.000	-0.862	0.396
Coordination	0.144	0.250	31.000	0.573	0.571

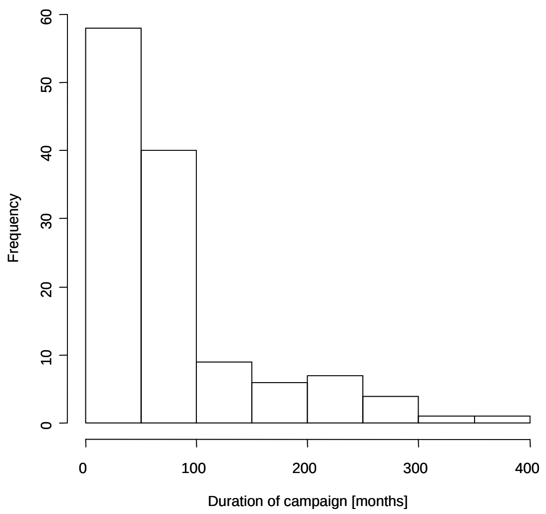


Figure 1: Frequency distribution of the duration of eradication campaigns, counted in months. Ongoing campaigns are counted until December 2008.

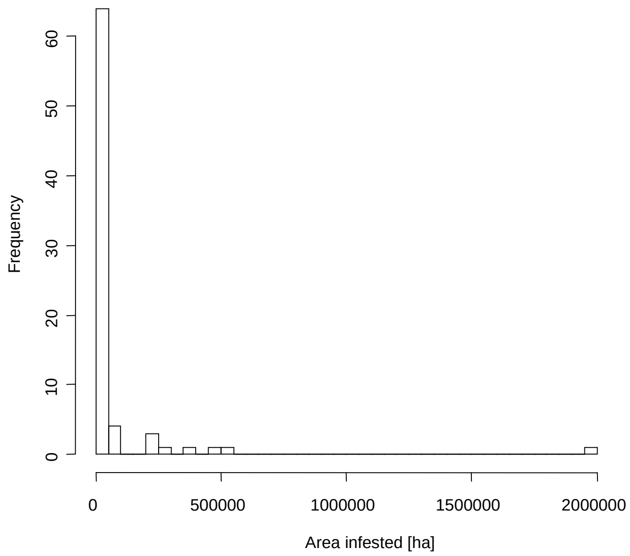
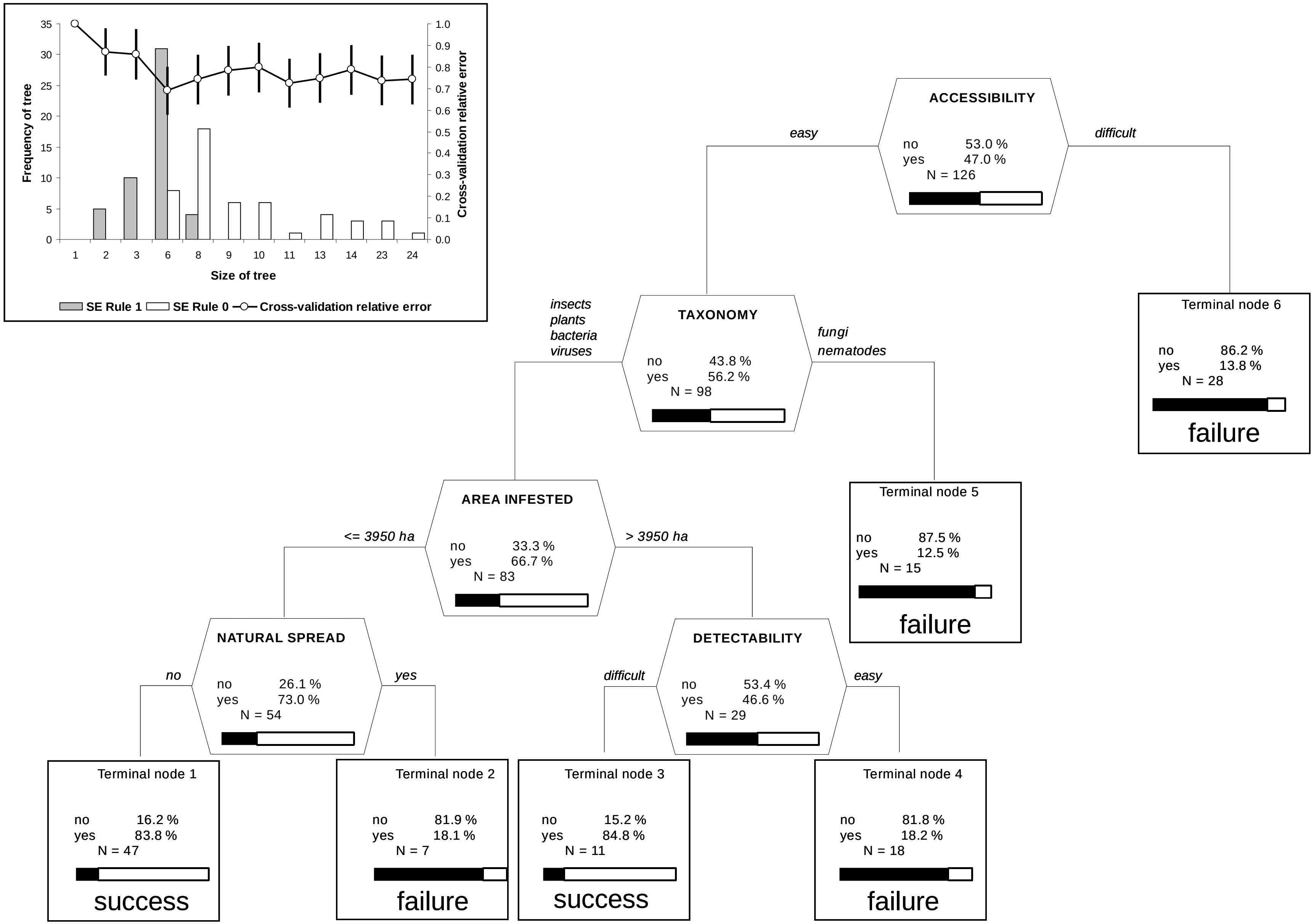


Figure 2: Frequency distribution of the size of the infested area in hectares.



Frequency of tree
Cross-validation relative error
Size of tree
SE Rule 1
SE Rule 0
Cross-validation relative error
ACCESSIBILITY
no 53.0 %
yes 47.0 %
N = 126
easy
difficult
TAXONOMY
no 43.8 %
yes 56.2 %
N = 98
insects
plants
bacteria
viruses
fungi
nematodes
Terminal node 6
no 86.2 %
yes 13.8 %
N = 28
failure
AREA INFESTED
no 33.3 %
yes 66.7 %
N = 83
<= 3950 ha
> 3950 ha
Terminal node 5
no 87.5 %
yes 12.5 %
N = 15
failure
NATURAL SPREAD
no 26.1 %
yes 73.0 %
N = 54
no
yes
DETECTABILITY
no 53.4 %
yes 46.6 %
N = 29
difficult
easy
Terminal node 1
no 16.2 %
yes 83.8 %
N = 47
success
Terminal node 2
no 81.9 %
yes 18.1 %
N = 7
failure
Terminal node 3
no 15.2 %
yes 84.8 %
N = 11
success
Terminal node 4
no 81.8 %
yes 18.2 %
N = 18
failure

Figure 3:
Classification tree for the success of eradication campaigns (yes/no). yes = The eradication campaign was successfully accomplished, no = all other campaigns. Polygons are splitting nodes, rectangles are terminal nodes. The names of the splitting variables are given above each splitting node. Each node includes a table showing the % of failed (no) and successful (yes) campaigns, the total number of unweighted cases (N) and graphical representation of the percentage of no (white) and yes (black) weighted cases in each class (horizontal bar). The vertical depth of each node is proportional to its improvement value that corresponds to the explained variance at the node.

Inset: Cross-validation processes to select the optimal regression tree. The line shows a single representative 10-fold cross-validation of the most frequent (modal) optimal tree with standard error (SE) estimates of each tree size. Bar charts are the numbers of the optimal trees of each size (Frequency of tree) selected from a series of 50 cross-validations based on the minimum cost tree, which minimizes the cross validated error (white, SE rule 0), and 50 cross-validations based on the 1–SE rule (grey, SE Rule 1), which minimizes the cross-validated error within one standard error of the minimum. The most frequent (modal) tree has six terminal nodes. Full summary and diagnostic information on the tree are in Appendices 4 and 5