Biol Invasions (2014) 16:401–414
DOI 10.1007/s10530-013-0529-5

ORIGINAL PAPER

Determinants of successful arthropod eradication programs

Patrick C. Tobin · John M. Kean · David Maxwell Suckling · Deborah G. McCullough · Daniel A. Herms · Lloyd D. Stringer

Received: 17 December 2012 / Accepted: 25 July 2013 / Published online: 27 August 2013

Abstract Despite substantial increases in public awareness and biosecurity systems, introductions of non-native arthropods remain an unwelcomed consequence of escalating rates of international trade and travel. Detection of an established but unwanted non-native organism can elicit a range of responses, including implementation of an eradication program. Previous studies have reviewed the concept of eradication, but these efforts were largely descriptive and focused on selected case studies. We developed a Global Eradication and Response DAtabase ("GERDA") to facilitate an analysis of arthropod eradication programs and determine the factors that influence eradication success and failure. We compiled data from 672 arthropod eradication programs targeting 130 non-native arthropod species implemented in 91 countries between 1890 and 2010. Important components of successful eradication programs included the size of the infested area, relative detectability of the target species, method of detection, and the primary feeding guild of the target species. The outcome of eradication efforts was not determined by program costs, which were largely driven by the size of the infestation. The availability of taxon-specific control tools appeared to increase the probability of eradication success. We believe GERDA, as an online database, provides an objective repository of information that will play an invaluable role when future eradication efforts are considered.

Keywords Detection · Eradication · Invasive species management · Non-native pests

Introduction

Despite increased attention and enhanced regulatory efforts, non-native organisms continue to become

P. C. Tobin (✉)
Forest Service, U.S. Department of Agriculture, Northern Research Station, Morgantown, WV 26505, USA
e-mail: ptobin@fs.fed.us

J. M. Kean
AgResearch Limited, Ruakura Research Centre, East Street, Private Bag 3115, Hamilton 3240, New Zealand

D. M. Suckling · L. D. Stringer
The New Zealand Institute for Plant & Food Research Limited, Private Bag 4704, Christchurch 8140, New Zealand

D. M. Suckling · L. D. Stringer
Plant Biosecurity Cooperative Research Centre, Canberra, ACT, Australia

D. G. McCullough
Departments of Entomology and Forestry, Michigan State University, 243 Natural Science Building, East Lansing, MI 48824, USA

D. A. Herms
Department of Entomology, Ohio Agricultural Research and Development Center, The Ohio State University, 1680 Madison Ave., Wooster, OH 44691, USA

established in new regions, primarily as a result of the increasing volume and shifting patterns of international travel and trade (Aukema et al. 2010; Hulme et al. 2008; Levine and D'Antonio 2003; Reichard and White 2001). Many countries maintain border biosecurity systems designed to detect and intercept species arriving through trade and travel routes before these organisms can become established. However, the sheer volume of global trade and travel, and the diversity of invaders, makes it inevitable that some species will evade detection at ports-of-entry, and a portion of those species will become established (Brockerhoff et al. 2006; Liebhold et al. 2012; National Research Council 2002; Work et al. 2005). When a non-native species is detected, consequent management options range from taking no action to implementing an eradication effort. The concept of eradication is beguiling; it suggests a final and permanent solution to the threat of an invader. In practice, however, the deliberate extirpation of a target species can be challenging, both biologically and economically (Myers et al. 2000; Popham and Hall 1958). Moreover, because propagule pressure tends to be positively associated with establishment success (Drake and Lodge 2006; Lockwood et al. 2005; Simberloff 2009), successful eradication of a target species could be ephemeral if propagule pressure is not mitigated.

Past work has highlighted a number of conditions thought to be critical for an eradication program to be successful (e.g., Brockerhoff et al. 2010; Dahlsten and Garcia 1989; Hoffmann et al. 2011; Knipling 1966; Myers et al. 2000; Pluess et al. 2012a; Pluess et al. 2012b; Simberloff 2003; Simberloff et al. 2005). Attributes include the ability to detect, identify and monitor an invader, understanding the potential risks and impacts posed by the invader, and having the tools to respond rapidly and effectively. Policy related attributes include the authority to intervene or take action on public and privately-owned lands, procurement of necessary funds, and the commitment and political will exhibited by affected stakeholders and the public in support of the eradication effort. As a result of these collectively complex and daunting requirements, and the notoriety of a few spectacularly failed attempts, the scientific and regulatory community has often viewed eradication with pessimism (e.g., Dahlsten 1986; Dahlsten and Garcia 1989; Myers et al. 1998; Whitten and Mahon 2005).

Despite an often negative perception of the viability of eradication efforts, the long-term benefits of successful eradication typically outweigh the costs of the program (Brockerhoff et al. 2010). A dispassionate analysis of the factors that have influenced the success of eradication programs could have tremendous practical utility and serve to inform and improve the decision-making process. In this paper, we sought to assess the importance and quantify the roles of various factors that affect eradication success of non-native arthropods by using a global database comprised of successful and failed eradication programs.

Previous reviews of attempts to eradicate non-native pest species have been largely descriptive and consist of either narratives of selected programs or generalized examples (e.g., Dahlsten and Garcia 1989; Graham and Hourrigan 1977; Myers et al. 1998; Myers et al. 2000; Popham and Hall 1958). In a recent quantitative study, Pluess et al. (2012a) used Generalized Linear Mixed Models to analyze a database of 136 eradication campaigns against a variety of terrestrial invertebrates, plants, and plant pathogens. They reported that local campaigns were more likely to succeed than regional or national programs. Other factors, including the level of biological information available about the target species, insularity, and reaction time did not significantly influence the rate of eradication success. In a subsequent classification tree analysis based upon 173 eradication campaigns, reaction time was identified as an important determinant of eradication success, along with habitat type and target taxon (Pluess et al. 2012b). The authors also highlighted the dearth of information on program costs and other socioeconomic factors in their data, which are generally considered to play major roles in the outcome of eradication campaigns.

To expand our understanding of the determinants of successful eradication programs, we acquired data from 672 eradication programs against arthropods that were undertaken around the world between 1890 and 2010. These data were compiled into a web-based Global Eradication and Response DAtabase ("GERDA," Kean et al. 2013) that we developed and hereby present. Although GERDA also currently contains data on eradication programs targeting other taxa (e.g., nematodes, fungi, molluscs), we focused our analysis specifically on arthropods to avoid comparing taxa that differ vastly in their respective biology and invasion ecology. In addition to the current analysis presented in this paper, a long term goal of GERDA is to provide a repository to facilitate the ongoing collection and transfer of knowledge among biosecurity practitioners and the scientific community.

Materials and methods

Compilation of data

We compiled a database of eradication attempts targeting a total of 130 non-native arthropod species implemented in 91 countries (Fig. 1). The species targeted for eradication were generally defined as actionable pests in that their expected economic and ecological harm was sufficiently great to warrant an eradication attempt. We acquired data from a variety of sources including scientific literature, government documents and press releases, unpublished reports and other components of the grey literature, searches of reputable internet sites (i.e., those associated with universities or government agencies), and interviews with biosecurity personnel. The arthropod eradication data used for our analysis is documented by 453 references, all of which are recorded in GERDA.

One major challenge we encountered when compiling these data was defining whether or not a management activity constituted an "eradication attempt." To be included in GERDA, an eradication program had to satisfy the following three conditions:

1. *Management intent* Eradication, defined as the complete removal of the target species from a defined area, had to be identified as a goal of the program. Pest management programs were excluded if the objectives included reduction or containment, but not local extinction, of the target population. One of the greatest technical challenges of any eradication campaign is demonstrating the absence of the very last target individual; mere pest reduction, rather than complete extirpation, thus omits one of the most important aspects of eradication. However, we did encounter a few cases where eradication was fortuitously achieved following large-scale pest reduction programs. We included data from these cases because they provided valuable information regarding the effort and expenditures required to achieve eradication. Also, some newly-discovered incursions were managed initially for containment while information was gathered to evaluate potential costs, benefits, and feasibility of eradication. Such cases were not included unless there was evidence that the management goal changed from containment to eradication.
2. *Spatial distinctness* Eradication programs were considered unique when populations of a target pest occupied discrete areas separated by more than twice the typical dispersal distance of the target species, although in most cases the distances were far greater. In such cases, we argue that while the eradication effort was directed at the same target pest, programs targeting individual populations would have proceeded irrespective of other populations and therefore, each was uniquely informative. Some eradication programs against *Lymantria dispar* (L.) in North America (Hajek and Tobin 2009), for example, met this

Fig. 1 Country representation of arthropod eradication programs currently within GERDA

criterion. Conversely, an eradication program against *Teia anartoides* (Walker) in New Zealand (1999–2006) that targeted three population epicenters was considered as one program because each epicenter was close enough to be within the dispersal capability of male moths (Suckling et al. 2007). It was not always possible to deduce from the available data whether one large eradication program constituted several independent local programs; in these cases, we considered the program as a single effort. It was also sometimes difficult to determine if eradication programs against the same taxon in adjoining geopolitical areas (e.g., across US or Australian states) represented distinct and unique programs. In these cases, programs were included separately when separate management agencies were responsible for the program, or considered as one program when the management action was conducted under the auspices of a common agency.

3. *Temporal distinctness* The International Standards for Phytosanitary Measures Number 9 (Food and Agricultural Organization of the United Nations 2006) specifies that "the minimum period of time of pest freedom to verify eradication will vary according to the biology of the pest, but should take into consideration factors such as sensitivity of detection technology, ease of detection, life cycle of the pest, climatic effects, and efficacy of treatment." Under current international standard practices, declaration of eradication of most pests can be made provided that suitable surveillance activity has resulted in no subsequent detections for at least 2–3 times the normal generational time of the target taxon. We followed this convention whenever there was doubt about whether a subsequent detection in a previously treated area constituted a new invasion or an unsuccessful eradication.

GERDA data fields

A summary of data fields included in GERDA is presented in Table 1. Most fields were not challenging to populate since they were based on various taxonomic details and basic life history of the target taxon, geographic location of the eradication program and its climate, and details of the agency responsible for the program. Data that were more difficult to obtain, at times resulting in missing data fields, included the method of initial detection and specific treatments or tactics used for eradication. The most challenging data to acquire were the program costs. Even when expenditures were reported, they often only included direct costs of the treatment and not the total program cost (i.e., personnel, pre-treatment environmental assessments, public outreach and meetings). Of the 672 arthropod eradication programs used in this analysis, adequate cost data were available for 141 programs.

Standardization of costs

All cost data were converted to the 2005 United States dollar (USD) to allow for a direct comparison of eradication programs worldwide. To do this, historical annual average exchange rates were first used to convert local currencies to the USD (Officer 2011); USD amounts were then standardized to the year 2005. Various inflation rates can be applied for this standardization, some of which will inflate early years more than others (Williamson 2011). We used the GDP deflator, which "represents the mean price of all the goods and services produced in the economy" (Williamson 2011). Since eradication programs involve a combination of fixed and variable costs for labor and materials, the GDP deflator likely provides a more accurate index of cost than other methods, which generally rely on either the price of household consumables or the cost of unskilled labor.

Data analysis

Many of the quantitative and categorical variables from Table 1 were used in our analyses, and we merged some data fields or categories within a given data field. This reduced the frequency of missing data and minimized redundancy when categories within the field were conceptually equivalent. For example, when considering the size of the eradication program, we used the maximum extent of the regulated area, the maximum area treated, or the larger of the two values when both fields were populated. Due to the large number of target species that typically have a univoltine lifecycle, we considered species to be either "univoltine" or "not univoltine." The variables and their respective categories used in this analysis are

Table 1 A summary and description of the primary data fields currently included in the Global Eradication and Response DAtabase (GERDA)

Data field	Description (if applicable)
Full taxonomy	Order, family, genus, species, authority
Organism(s) impacted	Terrestrial plants, terrestrial animals, terrestrial ecosystems as a whole, aquatic ecosystems, stored products, timber, and other
Sector(s) impacted	Urban/ornamental/amenity, commercial/plantation forestry, other forests and woodlands, broad acre arable/cropping, horticulture, pastoral/rangeland, veterinary/medical, and/or other ecosystems
Host range (Niemelä and Mattson 1996)	Monophagous, oligophagous, or polyphagous
Relative detectability of the organism	High (distinctive), medium (typical), or low (cryptic)
Primary feeding guild (adapted from Hawkins and MacMahon 1989)	Leaf/stem chewer, sap sucker, leaf miner, gall former, phloem feeder, wood/stem borer, root feeder, inflorescence feeder, nectivore, frugivore, seed feeder, predator, parasite, parasitoid, omnivore/scavenger, or dung feeder
Reproductive strategy	Sexual, asexual, or heterogametic
Typical voltinism	Semivoltine, hemivoltine, univoltine, bivoltine, multivoltine, or varying substantially by region or population
Primary mode(s) of dispersal	Active flight, passive flight (windblown), crawling or walking, and/or human assisted
Typical mean rate of spread	<0.1, 0.1–1, 1–10, 10–100, or >100 km year^{-1}
Köppen climate group(s) of the extant range (Kottek et al. 2006)	Equatorial (Köppen A), arid (Köppen B), warm temperate (Köppen C), snow (Köppen D), or polar (Köppen E)
Köppen climate group of the eradication zone (Kottek et al. 2006)	Ibid
Geographic details of the eradication program	Country, state (where applicable), city, latitude and longitude of the epicenter of infestation
Date of initial detection	
Method of detection	Targeted traps or lures, untargeted (generalist) traps or lures, host or risk site searches, industry/scientific vigilance, or passive surveillance (i.e., public vigilance)
Agency responsible for program	
Free text details of probable mode of introduction and details of delimitation	
Stage of establishment	E.g., Still associated with introduction pathway, propagules found but no local population seen, local population established beyond introduction pathway, widespread and present for many generations
Maximum extent of the quarantine or movement control zone	km^2
Land use type(s) of eradication program	Industrial, residential, agricultural/forestry, natural ecosystems, and/or protected (e.g., greenhouse)
Assessment of risks	E.g., Significant impacts reported from elsewhere, potential impacts unknown but biologically feasible, direct impacts negligible but has trade implications, or negligible direct impacts expected but easily eradicable.
Management response	Eradication attempted, containment, pest management, no further action; in this analysis, only attempted eradications were included.
Reason for not attempting eradication	E.g., Pest already too widespread or abundant, lack of effective detection and/or control tools, open pathway for uncontrolled re-introduction, inability to contain the population while eradication tools are applied, not cost-effective, affected agencies are unable to reach a consensus, and/or other

Table 1 continued

Data field	Description (if applicable)
Start and end dates of eradication program	
Free text of monitoring details	
Control tool(s) used and number of applications	Pesticide, biopesticide, mass trapping, lure and kill, mating disruption, sterile insect technique, host removal/destruction, removal by hand, quarantine/movement control, release of natural enemies, and/or other
Control tool application method	E.g., Aerial application, ground application, baits, stem injection, soil drench, other
Start and end dates of control tool application	
Name of the pesticide, biopesticide, or active ingredient including dose	
Area treated	km^2
Total normalized cost	Entered as local currency and year, and automatically normalized to 2005 USD. See materials and methods for more information.
Free text details of how costs were shared among agencies (if applicable)	
Free text of any additional information not covered above	
Outcome	Eradication confirmed by adequate monitoring, eradication likely but not confirmed by adequate monitoring (but no additional reports of detection), eradication declared but subsequent evidence suggests it actually failed, or failure to eradicate
Free text for evidence of outcome	
Free text describing potential reasons for failure (if applicable)	E.g., budgetary limits, decline in political or social will, unable to detect or delimit infestations adequately, unable to access or treat all infestations, failure in control tools, available biological information was insufficient or inadequate

summarized in Table 2. Some variables were transformed using $\log_{10}$ to satisfy assumptions of normality (Table 2).

We first used logistic regression, using both forward and backward selection methods independently, to develop a subset of variables to explore further. The binary response variable was eradication success or failure (Table 2). Eradication programs in which the outcome was "in progress" or "unknown" were omitted in the logistic regression analysis (167 programs). Once we compiled a subset of variables through the stepwise technique, we used the likelihood ratio, G^2, to assess variable significance. Odds ratios, when appropriate, were formed after partitioning G^2 into non-significant components (Agresti 1996).

Separately, we used multiple correspondence analysis to assess the use of control tools by the taxonomic order of the target species to determine if certain orders were more frequently targeted with a specific control tool or set of tools. In this analysis, we focused on only five of the 13 orders currently included in GERDA (Coleoptera, Diptera, Hemiptera, Hymenoptera, and Lepidoptera), which collectively represented 617 eradication programs. Of the omitted orders, four contained only 1 or 2 eradication programs, while for the remaining four orders we lacked sufficient control tool information. We also used logistic regression to determine if eradication success differed among these five orders. Finally, we used least squares regression to analyze the relationship between the infested area (km^2) and the cost of the program (millions USD), after normalizing both variables using the $\log_{10}$ transformation. All analyses were conducted in SAS (1999).

Results

Summary information for all data currently in GERDA, including the data presented in this paper, are

Table 2 Variables from GERDA and their categories used in the logistic regression analysis

Data field	Categories used in the analysis
Climate suitability	(1) Favorable if the Köppen climate group of the native and non-native habitats overlapped; otherwise (2) unfavorable
Duration (transformed using $\log_{10}$)	Number of years between start and end dates
Host range	(1) Monophagous, (2) oligophagous, and (3) polyphagous
Infestation size, km^2 (transformed using $\log_{10}$)	Maximum extent of the quarantine or movement control zone OR Area treated OR the larger of the two
Method of detection	(1) Host/risk site searches and industry/scientific vigilance, (2) targeted traps or lures, (3) untargeted traps or lures and passive surveillance
Mode of spread	(1) Active or (2) passive
Number of control tool(s) used by category	(1) Pesticide, (2) biopesticide, (3) mass trapping and lure and kill, (4) host removal and removal by hand, (5) mating disruption, (6) sterile insect technique, (7) quarantine and movement control, and (8) release of natural enemies
Primary feeding guild	(1) Leaf/stem chewer and leaf miner, (2) root feeder, (3) sap sucker, (4) phloem feeder and wood/stem borer, (5) frugivore, (6) parasite and predator, and (7) omnivore/scavenger
Relative detectability of the organism	(1) High or (2) low
Typical mean rate of spread	Categorical: (1) <1, (2) 1–10, (3) 10–100, or (4) >100 km $year^{-1}$
Typical voltinism	(1) Univoltine or (2) not univoltine
Outcome (response variable)	(1) Eradication confirmed or likely eradicated and (2) failure to eradicate

available online (Kean et al. 2013); thus, we briefly summarize some of the characteristics of the database for arthropods. Of the 672 arthropod eradication programs considered in this analysis, 395, 110, and 167 were considered to be successful, a failure, or either in progress or unknown, respectively. The 167 programs either in progress or unknown were comprised of 68 species, of which 35 species were represented by one program, and 61 species were represented by <5 programs. The remaining 505 programs that were considered to be successful or a failure were comprised of 111 species.

Considering all 672 arthropod eradication programs, the most numerically-prevalent orders of target pests were Diptera (259 cases), Coleoptera (133 cases), Lepidoptera (133 cases), Hymenoptera (61 cases), and Hemiptera (31 cases). The most numerically prevalent target species were *L. dispar dispar* (L.) (73 cases), *Ceratitis capitata* (Wiedemann) (56 cases), *Bactrocera dorsalis* Hendel (40 cases), *Aedes aegypti* (L.) (33 cases), and *Agrilus planipennis* Fairmaire (25 cases). There were 112 target species for which the number of eradication programs was <10 and 51 species were targeted by only a single eradication program. A time series of the number of eradication programs by the year of commencement is presented in Fig. 2.

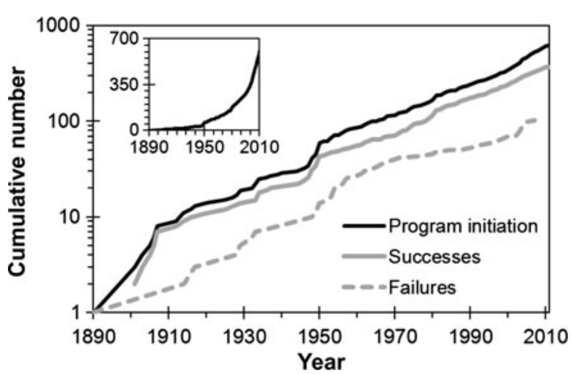

Fig. 2 Cumulative number of initiated eradication programs, and when programs were declared to be either successful or a failure (excluding programs in progress or if the outcome was not known), 1890–2010. The *insert* graph represents the total number of initiated programs on a non-transformed scale

The stepwise regression procedure initially identified the following variables as potentially significant predictors of eradication success: infestation size, method of detection, relative detectability of the organism, voltinism, program duration, host range, and primary feeding guild. In a subsequent full model with this subset of variables, duration and voltinism were not significant ($P > 0.3$). All other variables were significant ($P < 0.01$), and the Hosmer and Lemeshow lack-of-fit test was not significant ($P = 0.94$), suggesting that the full model would not be improved by the inclusion of additional variables. Because two species, *L. dispar dispar* and *C. capitata*, accounted for 10.9 and 8.3 % of the arthropod eradication programs, respectively, we also conducted our analysis with these two species excluded. In addition to both being the two most numerically dominant species, they also provided contrasting case examples, such as in the commodities affected (forest vs. agricultural), voltinism (univoltine vs. multivoltine), and feeding guild (folivore vs. frugivore). Following the stepwise regression procedure, the same variables were observed to be significant in this reduced dataset with the exception of one variable: the method of detection was not significant in this reduced dataset ($P = 0.39$).

An interesting aspect of these analyses was that the climate suitability variable was not significant due to the fact that eradication programs were rarely conducted in the absence of climate suitability. For example, in 95.1 % of the programs (N = 245 programs) in which we could confidently assign a Köppen climate group (Kottek et al. 2006) to both the native habitat of the target species and the habitat where the eradication program was conducted, the climate group overlapped. Furthermore, in only two cases was the level of climate mismatch by more than one climate group (i.e., Köppen C, warm temperate, to Köppen D, snow). The lack of climate suitability could result in a failure to establish following arrival and preclude the need to initiate eradication. Exceptions to this pattern could include pest species that can exploit climate-controlled environments, such as greenhouses, homes, and other structures.

The area of the eradication program, or infestation size, was both a significant predictor of the probability of eradication success ($P < 0.01$, N = 255, Fig. 3a) and program costs ($P < 0.01$, N = 141, Fig. 3b). Regarding eradication success, the odds of a successful eradication program were 1.3 times less likely (95 % CI 1.1–1.5) for every $\log_{10}$ increase in area. In terms of cost, we observed a positive relationship between area and cost [$\log_{10}$(costs, millions USD) = −0.254 + 0.416($\log_{10}$(area, km^2)); $R^2 = 0.52$]. We also illustrate separately eradication attempts against non-native forest insects for which our cost data were particularly robust (Fig. 3b). We did not observe a significant effect of outcome (i.e., success or failure, $P = 0.87$), or a significant interaction effect between area and outcome ($P = 0.87$) on costs. Moreover, we also did not detect a significant effect of target group (forest insects whose programs were dominated by those against *L. dispar*, versus other arthropods whose programs were dominated by those against *C. capitata* and *B. dorsalis*, $P = 0.53$), or a significant interaction effect between target group and area on costs ($P = 0.86$). Thus, the primary driver of program costs appears to be the area of the infestation and not the target group or the eventual program outcome.

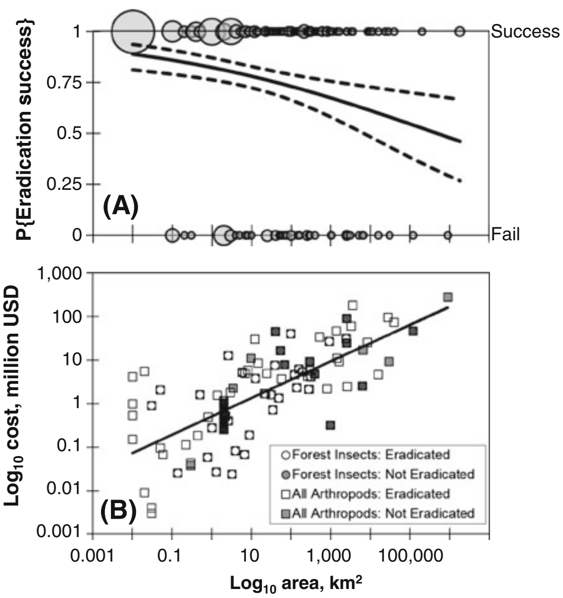

Fig. 3 Relationship between area of the infestation and the probability of eradication success (**a**), and the program costs (**b**). In **a**, the size of the circle reflects the number of cases, while the *solid* and *dashed lines* are the predicted probabilities and 95 % confidence intervals from logistic regression, respectively. In **b**, the *solid line* is the least squares regression fit to all arthropod data

The probability of eradication success was significantly affected by both the relative detectability of the target species ($P < 0.01$, Fig. 4a) and, when considering all species, the method of detection ($P < 0.01$, Fig. 4b). Because more than 95 % of target species in GERDA were classified as having either a high or low detectability, we excluded species that were classified as having a medium detectability. Generally, species were classified as having high detectability if a sensitive monitoring tool exists, such as traps baited with species-specific pheromones. Eradication programs were 8.1 times (95 % CI 3.9–16.6) more likely to be successful if the target species was classified as having a high, rather than a low, detectability. With regard to the method of detection, programs that used active methods, such as targeted traps using species-specific semiochemical attractants, were 4.6 times (95 % CI 1.4–15.4) more likely to result in eradication success than programs relying on passive detection methods (e.g., non-specific traps or public vigilance), and 26.8 times (95 % CI 9.6–74.6) more likely to result in eradication success than programs relying on host and habitat searches (Fig. 4b). Interestingly, programs that relied on passive detection methods were 5.9 times (95 % CI 2.0–17.4) more likely to be successful than those that relied on host or habitat searches. When *L. dispar dispar* and *C. capitata* were excluded, we did not detect a significant difference in the method of detection.

Host range of the target species significantly affected the probability of eradication success ($P < 0.01$, Fig. 5a). Polyphagous species were 6.2 times (95 % CI 3.6–10.6) more likely to be eradicated than the combined group of oligophagous and monophagous species, both of which were not significantly different ($P = 0.06$). This observation could be reflected by the number of programs that have targeted the polyphagous species *L. dispar*, *C. capitata*, and *B. dorsalis*, which collectively accounted for 169 programs. These species also represent high impact plant pests that are often aggressively targeted for eradication when detected, which could explain the higher success rate of eradication programs against polyphagous species.

The primary feeding guild also significantly affected the probability of eradication success ($P < 0.01$, Fig. 5b). Folivores and frugivores formed

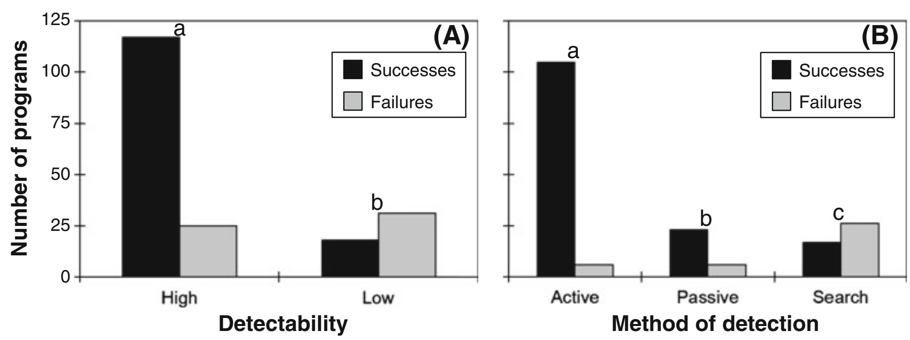

Fig. 4 Number of eradication programs that were successes or failures based upon the relative detectability of the target species (**a**) or the method of detection (**b**) (cf. Tables 1, 2). Different *lowercase letters* in **a**, **b** denote significant differences in eradication success ($P < 0.05$)

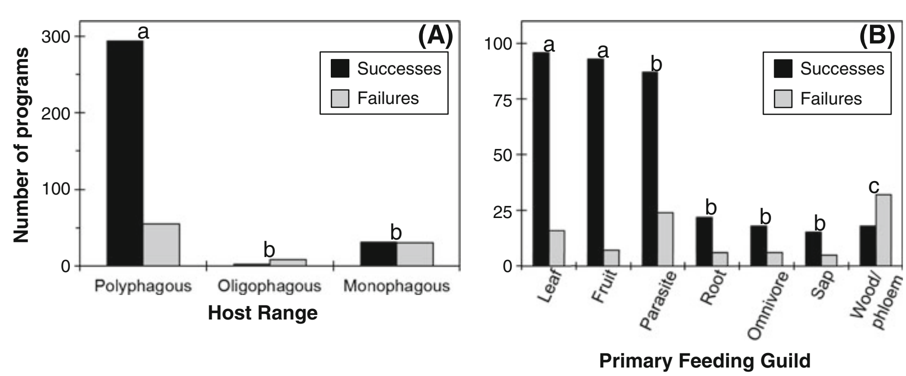

Fig. 5 Number of eradication programs that were successes or failures based upon the host range (**a**) and primary feeding guild (**b**) of the target species. Different *lowercase letters* in **a**, **b** denote significant differences in eradication success ($P < 0.05$)

a non-significant group ($P = 0.09$) and had the highest rate of eradication success, followed by parasites, root feeders, sap suckers, and omnivores, which formed a separate non-significant group ($P = 0.97$). Wood and subcortical phloem feeders had the lowest rate of eradication success and were 14.6 (95 % CI 7.1–30.1) and 6.2 (95 % CI 3.1–12.1) times less likely to be successfully eradicated than the combined group of folivores and frugivores, and the combined group of parasites, root feeders, sap suckers, and omnivores, respectively (Fig. 5b).

A multiple correspondence analysis revealed that in arthropod eradication programs the use of specific control tools differed significantly among orders ($P < 0.01$). When partitioning $\chi^2 \approx 89$ % of the variation was explained by two dimensions (Fig. 6). The most pronounced associations between insect orders and the control tools used for eradication were the use of mass trapping or lure and kill, and the sterile insect technique against Dipteran pests, and mating disruption and biopesticides against Lepidopteran pests (Fig. 6). Host removal and destruction were most often associated with programs against Coleoptera and Hemiptera (Fig. 6). The probability of successful eradication also differed significantly among orders ($P < 0.01$). For eradication programs targeting Lepidoptera (N = 115 programs) and Diptera (N = 189), for which there were specific available control tools, 86.1 and 86.8 %, respectively, were considered successful. In contrast, 71.4, 68.2, and 59.1 % of programs targeting Hymenoptera (N = 49 programs), Hemiptera (N = 22), and Coleoptera (N = 88), respectively, were considered to be successful. We recognize that reporting bias in favor of successful programs almost certainly exists, which could alter the proportion of programs deemed successful. However, given the extensive sample size and the fact that many control tools are linked to the biology of the targeted organisms, we contend that the varying levels of success observed for different orders is likely a robust pattern.

Discussion

The increase in eradication attempts beginning in the late 1980s (Fig. 2) could partially reflect an increased number of arrivals of non-native species (Levine and D'Antonio 2003; Liebhold et al. 2006; McCullough et al. 2006; Work et al. 2005). It could also reflect increased awareness of the inimical effects of some non-native species and technological advances leading to new or improved control tactics and strategies. Only a minority of introduced species cause substantial economic, social and ecological harm (Aukema et al. 2010; Mack et al. 2000), and eradication is rarely warranted unless the impacts of the non-native species are expected to be severe. We acknowledge sampling bias could exist in the temporal pattern of data compiled in GERDA given that more recent data

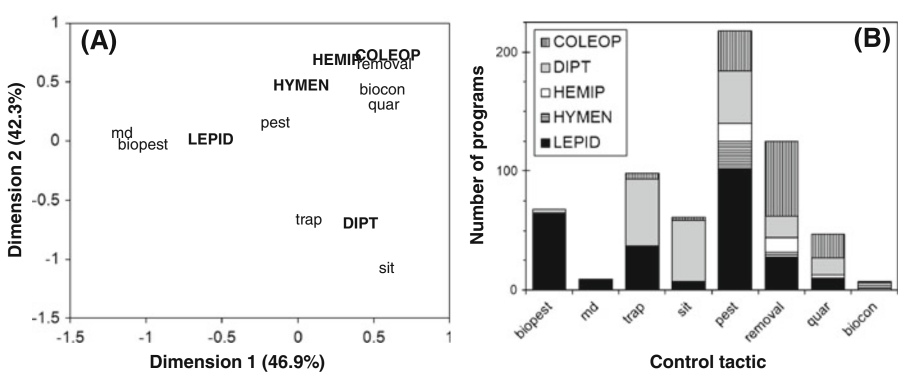

Fig. 6 **a** Multiple correspondence analysis of control tools used by order of target pests, showing variation primarily across two dimensions. The percentages indicate the percent variation explained by each respective dimension. **b** Corresponding plot of the number of programs, by order, that have used the indicated control tools. Orders are shown in uppercase (DIPT, Diptera; LEPID, Lepidoptera; HYMEN, Hymenoptera; HEMIP, Hemiptera; and COLEOP, Coleoptera) and control tools are shown in *lowercase* (sit, sterile insect technique; trap, mass trapping or lure and kill; biopest, biopesticide; md, mating disruption; pest, pesticide; removal, host or habitat removal; biocon, release of natural enemies; and quar, quarantine and movement control)

are easier to locate and compile, and that successful programs could be reported more often due to the reluctance to publicize failures. We contend, however, that the extensive database, which encompasses 672 arthropod eradication programs, is robust enough for this initial analysis of the primary drivers of eradication success and failure.

For a small proportion of potentially high impact, non-native pests, eradication could be cost-effective and the preferred management option for governments, providing that certain conditions are met. Our analysis, which encompassed many examples of eradication efforts targeting arthropod pests with diverse life history strategies, has revealed some consistent patterns. For example, the probability of eradication success declines as the area that is infested increases (Fig. 3a), a pattern that is both intuitive and reflected by prior observations (Liebhold and Tobin 2006; Pluess et al. 2012b; Rejmánek and Pitcairn 2002). Conversely, the cost of the eradication effort increases over the area that is infested (Fig. 3b), which likewise is intuitive. Quantification of the general relationships between the area of an infestation and the predicted probability of eradication success and program costs should be useful in future planning efforts when eradication is considered as a management response.

High relative detectability of the target species is a primary component of successful eradication programs (Fig. 4a). With regard to *L. dispar* eradication efforts, for example, there was a dramatic increase in eradication programs in North America following the identification and synthesis of the *L. dispar* sex pheromone (Bierl et al. 1970), which is now routinely used in *L. dispar* monitoring programs (Tobin et al. 2012). It is extraordinarily challenging to manage any species when the ability to detect the target species is limited, especially in an eradication program. Furthermore, the failure to detect small incipient populations caused by the lack of a sensitive survey tool could result in the infestation being larger when finally detected, and therefore, less likely to be successfully eradicated in an economically feasible manner (Fig. 3, Epanchin-Niell et al. 2012).

It was not unsurprising that the relative detectability of target pests was an important factor in eradication success. Programs that can rely on active methods of detection, such as species-specific lures and trapping devices, are most likely to be successful (Fig. 4b), reinforcing the importance of detection systems to improve invasive species management (Government Accountability Office 2006; Jarrad et al. 2011; Simberloff et al. 2005). Probability of success was also greater when passive means of detection, such as through private citizens reporting pest presence, were used rather than pre-emptively searching sites considered to be at high risk of species arrival (e.g., nurseries, industrial sites, sawmills), which was least likely to be associated with eradication success (Fig. 4b). This finding could reflect an overall increase in public awareness of non-native pests and the effectiveness of public relationship campaigns coordinated by universities, biosecurity and resource management agencies. The lack of significance of the method of detection when *L. dispar dispar* and *C. capitata* are excluded from the analyses could reflect the historical target trapping for these two pests. The availability of relatively inexpensive detection traps, and control tools, for both these high risk pests enables countries to maintain trapping networks and respond to detection with an eradication program. This likely explains the numerical dominance of *L. dispar dispar* and *C. capitata*. When these two species were excluded from the analyses, detection method was no longer significant, which could reflect insufficient variation in the method of detection represented by the remaining programs.

The detectability of target pests undoubtedly plays an important role at the end of an eradication program because it largely determines whether the apparent absence of a target pest represents eradication success. The reappearance of a species thought to be extinct, referred to as the “Lazarus effect” (Flessa and Jablonski 1983; Morrison et al. 2007), and has been implicated, for example, in the recurrence of *C. capitata* detections in California (Carey 1996; but see Liebhold et al. 2006). The inability to detect the last few remaining individuals of a population targeted for eradication, even in the face of aggressive detection efforts has important consequences in the analysis and interpretation of data from eradication programs. We attempted to minimize misclassifications of eradication success, such as those due to the Lazarus effect, by using a criterion of apparent absence of at least 2–3 times the normal generational time of the target taxon. Any remaining misclassifications would largely lie with the most numerically dominant taxa within GERDA; however, our results were largely unaffected when the two most dominant species, *L. dispar dispar* and *C. capitata*, were excluded, suggesting that potential Lazarus effects have not greatly affected our conclusions.

The importance of detectability could also be reflected in the primary feeding guild of the target species (Fig. 5). Damage caused by externally feeding arthropod folivores or frugivores is likely to be noticed, whereas more clandestine species that feed within their host plant are likely to escape detection for some time, at least during the early stages of the invasion process. Subcortical wood and phloem feeders have been a particularly challenging group to eradicate, reflecting their cryptic life history, often low detectability, and the lack of control options available for use over large areas. Research to develop better detection technology and control options for these organisms should be a priority, particularly given the sharp increase in new detections of non-native subcortical borers over the past 20–30 years (Langor et al. 2009; Aukema et al. 2010). The use of "citizen scientists" has also generated much interest with regard to a diversity of ecological research topics (see the recent special issue introduced by Henderson 2012). For example, in New Zealand, approximately half of all new plant pest detections are reported by the general public (Froud et al. 2008), and it is believed that every known *Anoplophora glabripennis* (Motschulsky) infestation in the USA was discovered by private citizens. The engagement of citizen scientists to aid in surveys for invasive pests is a promising management tool that deserves more attention (e.g., Beetle Busters 2012; Crall et al. 2010; Ingwell and Preisser 2011).

The ability to use taxon-specific tools in an eradication program also appears to be an important determinant of eradication success. Analysis of the current GERDA database reveals that Diptera and Lepidoptera had the highest rate of eradication success and both were strongly associated with more specific control tools, such as mass trapping, lure and kill, and the sterile insect technique (Diptera), or mating disruption and biopesticides formulated with the use of taxon-specific entomopathogens (Lepidoptera). In contrast, more general methods, such as host and habitat removal, tended to be associated with orders that have recorded less eradication success. Host-specific tactics could also benefit from wider societal acceptance if they are associated with fewer undesirable effects on the environment and to non-target organisms. The use of multiple tactics, especially those that are species-specific, that can act synergistically to decrease the target population could also lead to greater eradication success (Blackwood et al. 2012; Suckling et al. 2012).

We highlighted factors that are critical determinants of successful arthropod eradication programs, which should assist in the development of improved management responses to non-native species. Also, because we envision GERDA (Kean et al. 2013) as an online repository for eradication program data, the addition of new data could facilitate future analyses that provide greater insight into factors affecting the outcome of eradication programs. Indeed, since this manuscript was initially submitted, an additional 57 eradication programs and 25 non-native arthropod species that were not previously included have now been entered into GERDA. The inclusion of cost data for eradication programs, failed programs, and control tools used in the effort would greatly facilitate future analyses. Identifying constraints and determinants of success can provide a basis for prioritizing and enhancing future eradication attempts. Moreover, we anticipate that GERDA will help to inform biosecurity practitioners and the larger scientific community by providing rapid access to the experiences of others in the decision making process.

Acknowledgments This work was conducted as part of a working group, "Applying population ecology to strategies for eradicating invasive forest insects," supported by the National Center for Ecological Analysis and Synthesis (http://www.nceas.ucsb.edu/), a Center funded by NSF (Grant No. EF-0553768), the University of California, Santa Barbara, the State of California and the USDA Forest Service, Eastern Forest Environmental Threat Assessment Center, Asheville, North Carolina. We are very grateful to the numerous colleagues and biosecurity practitioners who assisted in the compilation of data on their respective eradication programs. We thank Laura Blackburn (USDA Forest Service) for technical assistance. We also acknowledge support from New Zealand's Better Border Biosecurity research program (b3nz.org) and an Australian Government's Cooperative Research Centre (www.pbcrc.com.au). We are grateful to three anonymous reviewers for constructive comments.

References

Agresti A (1996) An introduction to catagorical data analysis. John Wiley and Sons, Inc., New York, NY

Aukema JE, McCullough DG, Von Holle B et al (2010) Historical accumulation of nonindigenous forest pests in the continental US. Bioscience 60:886–897

Beetle Busters (2012). USDA animal and plant health inspection service. http://beetlebusters.info/. Accessed 23 October 2012

Bierl BA, Beroza M, Collier CW (1970) Potent sex attractant of the gypsy moth: its isolation, identification and synthesis. Science 170:87–89

Blackwood JC, Berec L, Yamanaka T et al (2012) Bioeconomic synergism between tactics for insect eradication in the presence of Allee effects. Proc R Soc Biol Sci Ser B 279:2807–2815

Brockerhoff EG, Bain J, Kimberley M et al (2006) Interception frequency of exotic bark and ambrosia beetles (Coleoptera: Scolytinae) and relationship with establishment in New Zealand and worldwide. Can J For Res 36:289–298

Brockerhoff EB, Liebhold AM, Richardson B et al (2010) Eradication of invasive forest insects: concept, methods, costs and benefits. N Z J Sci 40(Suppl.):S117–S135

Carey JR (1996) The incipient Mediterranean fruit fly population in California: implications for invasion biology. Ecology 77:1690–1697

Crall AW, Newman GJ, Jarnevich CS et al (2010) Improving and integrating data on invasive species collected by citizen scientists. Biol Invasions 12:3419–3428

Dahlsten DL (1986) Control of invaders. In: Mooney HA, Drake JA (eds) Ecology of biological invasions of North America and Hawaii. Springer-Verlag, New York, pp 275–302

Dahlsten DL, Garcia R (1989) Eradication of exotic pests: analysis with case histories. Yale University Press, New Haven

Drake JA, Lodge DM (2006) Allee effects, propagule pressure and the probability of establishment: risk analysis for biological invasions. Biol Invasions 8:365–375

Epanchin-Niell RS, Haight RG, Berec L et al (2012) Optimal surveillance and eradication of invasive species in heterogeneous landscapes. Ecol Lett 15:803–812

Flessa KW, Jablonski D (1983) Extinction is here to stay. Paleobiology 9:315–321

Food and Agricultural Organization of the United Nations (2006) International standards for phytosanitary measures no. 1 to 24. Secretariat of the international plant protection convention. Food and Agricultural Organization, Rome, p 291

Froud KJ, Oliver TM, Bingham PC et al (2008) Passive surveillance of new exotic pests and diseases in New Zealand. In: Froud KJ, Popay IA, Zydenbos SM (eds) Surveillance for biosecurity: pre-border to pest management. New Zealand Plant Protection Society, Christchurch, pp 97–110

Government Accountability Office (2006) Invasive forest pests. Lessons learned from three recent infestations may aid in managing future efforts. Government Accountability Office, Report to the Chairman, Committee on Resources, House of Representatives, GAO-06-353

Graham OH, Hourrigan JL (1977) Eradication programs for the arthropod parasites of livestock. J Med Entomol 13:629–658

Hajek AE, Tobin PC (2009) North American eradications of Asian and European gypsy moth. In: Hajek AE, Glare TR, O'Callaghan M (eds) Use of microbes for control and eradication of invasive arthropods. Springer, New York, pp 71–89

Hawkins CP, MacMahon JA (1989) Guilds: the multiple meanings of a concept. Annu Rev Entomol 34:423–451

Henderson S (2012) Citizen science comes of age. Front Ecol Environ 10:283

Hoffmann B, Davis P, Gott K et al (2011) Improving ant eradications: details of more successes, a global synthesis and recommendations. Aliens 31:16–23

Hulme PE, Bacher S, Kenis M et al (2008) Grasping at the routes of biological invasions: a framework for integrating pathways into policy. J Appl Ecol 45:403–414

Ingwell LL, Preisser EL (2011) Using citizen science programs to identify host resistance in pest-invaded forests. Conserv Biol 25:182–188

Jarrad F, Barrett S, Murray J et al (2011) Ecological aspects of biosecurity surveillance design for the detection of multiple invasive animal species. Biol Invasions 13:803–818

Kean J, Tobin P, Lee D et al (2013) Global eradication and response database. http://b3.net.nz/gerda. Accessed 18 June 2013

Knipling EF (1966) Some basic principles of insect population suppression and management. Bull Entomol Soc Am 12:7–15

Kottek M, Grieser J, Beck C et al (2006) World Map of the Köppen-Geiger climate classification updated. Meteorol Z 15:259–263

Langor D, DeHaas L, Foottit R (2009) Diversity of non-native terrestrial arthropods on woody plants in Canada. Biol Invasions 11:5–19

Levine JM, D'Antonio CM (2003) Forecasting biological invasions with increasing international trade. Conserv Biol 17:322–326

Liebhold AM, Tobin PC (2006) Growth of newly established alien populations: comparison of North American gypsy moth colonies with invasion theory. Popul Ecol 48:253–262

Liebhold AM, Work TT, McCullough DG et al (2006) Airline baggage as a pathway for alien insect species invading the United States. Am Entomol 53:48–54

Liebhold AM, Brockerhoff EG, Garrett LJ et al (2012) Live plant imports: the major pathway for forest insect and pathogen invasions of the United States. Front Ecol Environ 10:135–143

Lockwood JL, Cassey P, Blackburn T (2005) The role of propagule pressure in explaining species invasions. Trends Ecol Evol 20:223–228

Mack RN, Simberloff D, Lonsdale WM et al (2000) Biotic invasions: causes, epidemiology, global consequences, and control. Ecol Appl 10:689–710

McCullough DG, Work TT, Cavey JF et al (2006) Interceptions of nonindigenous plant pests at US ports of entry and border crossings over a 17-year period. Biol Invasions 8:611–630

Morrison SA, Macdonald N, Walker K et al (2007) Facing the dilemma at eradication's end: uncertainty of absence and the Lazarus effect. Front Ecol Environ 5:271–276

Myers JH, Savoie A, van Randen E (1998) Eradication and pest management. Annu Rev Entomol 43:471–491

Myers JH, Simberloff DS, Kuris AM et al (2000) Eradication revisited: dealing with exotic species. Trends Ecol Evol 15:316–320

National Research Council (2002) Predicting invasions of nonindigenous plants and plant pests. National Academy Press, Washington, DC
Niemelä P, Mattson WJ (1996) Invasion of North American forests by European phytophagous insects. Bioscience 46:741–753
Officer LH (2011) Exchange rates between the United States dollar and forty-one currencies. MeasuringWorth. http://www.measuringworth.com/exchangeglobal. Accessed 23 October 2012
Pluess T, Cannon R, Jarošík V et al (2012a) When are eradication campaigns successful? A test of common assumptions. Biol Invasions 14:1365–1378
Pluess T, Jarošík V, Pyšek P et al (2012b) Which factors affect the success or failure of eradication campaigns against alien species? PLoS ONE 7:e48157
Popham WL, Hall DG (1958) Insect eradication programs. Annu Rev Entomol 3:335–354
Reichard SH, White P (2001) Horticulture as a pathway of invasive plant introductions in the United States. Bioscience 51:103–113
Rejmánek M, Pitcairn MJ (2002) When is eradication of exotic pest plants a realistic goal? In: Veitch CR, Clout MN (eds) Turning the tide: the eradication of invasive species. IUCN, Gland, pp 94–98
SAS Institute, Inc. (1999) SAS/STAT® user's guide, Version 8. SAS Institute, Inc., Cary, NC
Simberloff D (2003) How much information on population biology is needed to manage introduced species. Conserv Biol 17:83–92
Simberloff D (2009) The role of propagule pressure in biological invasions. Annu Rev Ecol Evol Syst 40:81–102
Simberloff D, Parker IM, Windle PN (2005) Introduced species policy, management, and future research needs. Front Ecol Environ 3:12–20
Suckling DM, Barrington AM, Chhagan A et al (2007) Eradication of the Australian painted apple moth *Teia anartoides* in New Zealand: trapping, inherited sterility, and male competitiveness. In: Vreysen MJB, Robinson AS, Hendrichs J (eds) Area-wide control of insect pests: from research to field implementation. Springer, Dordrecht, pp 603–615
Suckling DM, Tobin PC, McCullough DG et al (2012) Combining tactics to exploit Allee effects for eradication of alien insect populations. J Econ Entomol 105:1–13
Tobin PC, Bai BB, Eggen DA et al (2012) The ecology, geopolitics, and economics of managing *Lymantria dispar* in the United States. Int J Pest Manag 53:195–210
Whitten M, Mahon R (2005) Misconceptions and constraints. In: Dyck VA, Hendrichs J, Robinson AS (eds) Sterile insect technique, principles and practice in area-wide integrated pest management. Springer, Dordrecht, pp 601–626
Williamson SH (2011) Seven ways to compute the relative value of a U.S. dollar amount, 1774 to present. MeasuringWorth. http://www.measuringworth.com/uscompare. Accessed 23 October 2012
Work TT, McCullough DG, Cavey JF et al (2005) Arrival rate of nonindigenous insect species into the United States through foreign trade. Biol Invasions 7:323–332