TRENDS IN ARTHROPOD ERADICATION PROGRAMMES FROM THE GLOBAL ERADICATION DATABASE, GERDA

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SUMMARY

The Global Eradication and Response Database (GERDA, <http://b3.net.nz/gerda>) documents representative incursion responses and eradication attempts against tephritid fruit flies of economic importance, Lepidoptera, tsetse flies, screwworm flies, mosquitoes, ants, beetles and other particular taxa of invasive arthropods since 1869. It includes cases where governments were quickly resigned to the inability to eradicate, as well as cases where a positive outcome was sought in a declared eradication programme. The distribution of pests is expanding well beyond what has been recorded in GERDA, but this information contains useful trends. The rate of eradication attempts continued to rise during the 20th and into the 21st century. In the case of Lepidoptera other than gypsy moth, 75% of programmes were started in the last 20 years. This is evidence for the rapid geographic range expansion under globalisation. It also indicates how active risk analysis and improved technology are increasingly enabling governments to attempt eradication to avoid projected substantial long-term costs of pest establishment. More than 80% of eradication programmes have been successful for arthropods in the database. For certain groups such as tephritid fruit flies of economic importance, the success rate is even higher, due to the experience gained from previous similar programmes, as well as the progress in the development of lures and suppression tools. A steady increase in the number of eradication programmes globally suggests that current exclusion measures for constraining the spread of invasive species are not adequate. Cost-benefit analysis based on prior pest behaviour indicates that additional mitigation against certain taxa are warranted (if possible). It is likely that all these reasons have led to this increase in the number of eradication programmes over time as a consequence of increases in travel and trade volumes from an expanding number of countries, a desire to maintain or reduce pest pressure on exotic and native commodities, and the development of new tools to increase the technical feasibility of eradication attempts. It is notable that arthropod eradication programmes still rely significantly on insecticides, but their importance is steadily decreasing when compared to the application of other tools.

Key Words: GERDA, eradication attempts, incursion responses, globalisation, invasive species, arthropods, alien, non-indigenous, risk analysis

1. INTRODUCTION

Invasive insect pest species are spreading as a consequence of increasing global trade and continue to emerge as a threat to food production and ecosystem health (Liebhold et al. 2016). This includes insect pests that need to be controlled to avoid significant losses in cropping systems in all regions of the world (Vreysen et al. 2016). Failure to manage these species would have serious consequences for food production worldwide (Vreysen et al. 2007). Some pests have already become ubiquitous global pests, but many are still undergoing geographic range expansion (EPPO 2018). There are sometimes arguments over what constitutes the current range of some species, such as the debate over whether tephritid fruit flies have established below detectable levels in California (McInnis et al. 2017; Carey et al. 2017; Shelly et al. 2017). There is also evidence of a problem of “fake news” in at least one eradication programme in California (Lindeman 2013).

Government-led incursion response programmes can have either eradication or sometimes just delimitation and containment as the goal. Governments often conduct a risk analysis to assess whether the establishment of the unwanted organism is likely to exceed an economic, environmental or social impact threshold and require an attempt to eradicate (Tobin et al. 2014). As part of a project identifying factors affecting outcomes from arthropod eradication efforts (Tobin et al. 2014; Liebhold et al. 2016), a global eradication database called “GERDA” (Kean et al. 2017) has been collating official incursion response programmes that can range from doing nothing through attempting eradication.

GERDA input is based on volunteerism, and registration for a login to access the data is free. GERDA contains information on 1139 incursion responses, of which 1037 led to eradication attempts (Kean et al. 2017). While this is not a complete list of all global incursion response data, data are continuously being verified and entered into the online database. More than 430 registered users of GERDA are listed, from 43 countries. The base data are available along with references so that entries can be checked.

The GERDA data have been contributed by many individuals, who share the vision of everyone having access to information that will facilitate better decision-making with respect to incursion responses. The data, scope and definitions used in the database are available (e.g. Box 1, Kean et al. 2017) and have been used to review global trends (Tobin et al. 2014), as well as details for particular taxa. For example, 28 lepidopteran species were the target of 144 known government-led incursion responses, with effort spread across 12 moth families, dominated by the *Lymantriinae* and *Tortricidae* (Suckling et al. 2017). Likewise, Suckling et al. (2016) reviewed the eradication of fruit flies of economic importance covering more than 200 programmes across 16 species.

In this paper, we reinvestigated the database for trends in 811 arthropod eradications in 94 countries, with an additional 63 programmes added since Tobin et al. (2014).

2. RESULTS

2.1. *Summary of Known Arthropod Eradications*

To August 4, 2017, the database reported 1093 incursion responses including 972 eradication programmes in 105 countries, targeting 309 taxa, of which 166 were arthropods. A total of 768 arthropod eradication programmes have been recorded. Of the 634 arthropod programmes for which the outcome is known, 514 (81%) were successful and 120 (19%) failed. The number of arthropod eradication programmes initiated climbed rapidly through the second half of the 20th century (Fig. 1).

Box 1. GERDA: Frequently Asked Questions

(Kean et al. 2017 (GERDA, <http://b3.net.nz/gerda/faq.php>)

The word "eradicate" originates from the Latin "to uproot" (*eradicator*). In ecology, eradication is the intentional local extinction, or extirpation, of a particular taxon. This involves the killing or complete removal of every individual of a population of the target taxon from a defined area, i.e. achieving population size zero.

The target taxon is most often a population of a species but may sometimes be a subspecies or more than one closely related species. Eradication programmes almost always target populations of pestiferous invasive species in part of their invaded range.

The target area for an eradication programme may vary greatly in size. Often eradications are carried out in geographically-isolated areas, such as islands, to minimise the risk of reintroduction. Sometimes, however, eradications may target a particular part of a species' range because of the environmental, economic, or political benefits of removal, even if the species is likely to reinvade.

One of the biggest challenges of any eradication programme is demonstrating success. The International Plant Protection Convention (IPPC) specifies standards for plant pest eradications in its International Standards for Phytosanitary Measures No. 9 (FAO 2016a), but these are largely descriptive. Current international practice specifies that, provided that adequate surveillance activity has been carried out, eradication of most plant pests can be declared once there have been no detections for at least three times the normal generation time of the target taxon (FAO 2016b; Kean et al. 2017).

Of the 768 arthropod eradication programmes recorded so far in GERDA, the method of pest detection is known for 42% of the entries. A range of detection methods led to the start of these programmes (Fig. 2), of which more than half were based on specific traps and lures (e.g. pheromones). In contrast, insect traps without specific lures (e.g. a light trap) have not been the primary tool for detection of a pest that has subsequently been subjected to an eradication programme.

2.2. *Clustering of Arthropod Eradications*

Certain orders of insects were more frequently targeted for eradication, especially Diptera (Tephritidae and Culicidae in particular), followed by Coleoptera and Lepidoptera (Table 1). This is likely due to the potential significant impact that species from these groups have on primary agricultural production and human health, as well as the availability of eradication tools (Suckling 2015).

Figure 1. Arthropod eradication programmes initiated each decade, reported in the Global Eradication and Response Database, GERDA (<http://b3.net.nz/gerda>) (accessed August 4, 2017). *Data for this decade are from January 2010 until August 4, 2017.

Figure 2. The number of times various detection methods led to the initiation of arthropod eradication programmes stated in the Global Eradication and Response Database (updated from Kean et al. 2017).

GERDA shows evidence of the same clusters forming around similar arthropod taxa as can be found in a database on attractants for pest management (Suckling 2015; El-Sayed 2018). GERDA illustrates the complexity of the different life histories that must be sufficiently understood before engaging in eradication attempts.

Once detection trapping systems are developed, it is frequently possible to use knowledge from previous programmes against similar threats to gain efficiencies. Some methods are applicable over a range of different taxa, whereas in other cases, methods available for closely related species can be easily adapted.

A number of major taxa showed a high degree of re-occurrence as targets of eradication programmes (Table 1; Fig. 3).

Table 1. Number of eradication programmes so far recorded in the Global Eradication and Response Database (GERDA) and success rate by insect order (August 4, 2017)

Order	Count	% Likely or Confirmed Eradication
Diptera	331	77.6
Coleoptera	139	42.4
Lepidoptera	135	75.5
Hymenoptera	70	62.8
Hemiptera	34	50.0
Isoptera	18	38.9
Thysanoptera	11	64.0
Other	33	72.0
Total	768

Figure 3. Percentage of successful arthropod eradication programmes by major target taxon (from GERDA, updated from Kean et al. 2017).

The eradication success rate was relatively high for most major target taxa. However, success rates were lower for weevils and buprestid beetles, notably the emerald ash borer, *Agrilus planipennis* Fairmaire (Buprestidae), which has proven difficult to eradicate with the current tools available. About 60% of tick (Ixodidae) and tsetse fly (Glossinidae) eradication programmes were successful, followed by ants (Formicidae) and mosquitoes (Culicidae), longhorn beetles (Cerambycidae), tussock moths (Erebidae), leaf beetles (Chrysomelidae) and fruit flies (Tephritidae) (Fig. 3). The few thrips were largely in glasshouse situations.

We acknowledge that the GERDA data probably contain some reporting bias, but contend that the results are nevertheless indicative of a trend whereby some insect taxa are more easily eradicated than others, due to their biology, invasion dynamics or the tools available to detect and manage them.

The clustering of certain targets at different taxonomic levels, such as the Tephritidae within the Diptera, rather than representatives of all families within the Diptera, indicates the patchiness of pests in certain taxonomic and economic clusters. Even though flies have a broad range of hosts, the vast majority are not pests, apart from those with fruit, animals or humans as hosts, which are well represented in the eradication data as targets on multiple occasions.

2.3. Increase in the Number of Arthropod Eradication Programmes

The annual number of eradication programmes across all invasive arthropods has increased steeply in recent decades (Fig. 1), but this has been accompanied by the development of more specific, environmentally-friendly and cost-effective tools. In fact, the sub-family Lymantriinae demonstrate how, with the development of new tools, patterns of eradications attempts can change. The 74 *Lymantria dispar* L. entries in GERDA are USA-dominated due to the “Slow the Spread Programme” for *L. dispar* in the USA (Sharov et al. 2002). For the 61 programmes against this pest for which the control tools are known, initial eradication and management attempts in the late 19th and early 20th centuries consisted of picking of egg masses by hand as one of the few options available (Myers et al. 2000). This was followed by the spraying of persistent insecticides, which showed a steady increase until the 1960s, when efforts were made to develop alternative control methods, such as mass-trapping approaches (Fig. 4).

The synthesis of the sex pheromone for *L. dispar* enabled the delimitation and monitoring of populations through the trapping of male moths attracted to traps (Bierl et al. 1970). Then in the 1980s, the biopesticide, *Bacillus thuringiensis kurstaki*, was extensively trialled in the USA for use against Lepidoptera (USFS 1994). Also, at this time, mating disruption became more readily available (Cardé, this volume), after being tested and reported from the late 1970s (Schwalbe et al. 1979). In addition, a number of Sterile Insect Technique (SIT) field trials were successfully conducted against gypsy moth in the 1970s and 1980's, but it was concluded that the method was not cost-effective (Simmons et al. 2021).

In the 1970's and 1980's there was a rapid increase in the number of *L. dispar* eradication attempts (Fig. 4). The biopesticide is now the only tool recorded as used for eradication for the past 20 years, probably because it is cheap to apply, and a large amount of the moth's range is over forested areas, so few people are affected by application, thus not opposed to its use. The effectiveness of the biopesticide and the acceptability of its use, is probably the reason why there has been a shift from multiple tools used in earlier years, to a single tool used in recent years for the eradication of *L. dispar* (Fig. 4).

Figure 4. The type of suppression tools used for 61 *Lymantria dispar* eradication programmes over time. Physical removal includes both removal of host and hand removal of the pest; odour-based includes mass-trapping, lure and kill, and mating disruption (from GERDA, updated from Kean et al. 2017).

However, urban-based eradication can face public opposition to aerial use of the biopesticide, so mass-trapping, mating disruption used with reduced rates (Tcheslavskaia et al. 2005), or sterile insect release can present more favourable options (Gamble et al. 2010). In fact, mating disruption is widely used in the “Slow the Spread Programme” (Tcheslavskaia et al. 2005; Liebhold et al. this volume), although details of this suppression programme on the leading edge of gypsy moth infestation are not reported in GERDA due to its focus on eradication programmes.

It is not possible to identify a single cause of the increase in the number of arthropod eradication and response programmes, but it is likely due to a combination of several factors, including the ability to monitor and detect introduced pest populations with their sex pheromone, from the 1970s.

With the development of better or more publicly-accessible pest control technologies throughout time, a corresponding change in the type of management methods used is expected, and this appears to be the case (Fig. 5).

Figure 5. The number of programmes using different tools to eradicate populations of arthropods. Note some programmes used multiple tools. Physical removal includes both removal of host and hand removal of the pest; odour-based includes mass-trapping, lure and kill, and mating disruption (from GERDA, updated from Kean et al. 2017).

Insecticides still feature heavily in arthropod eradications, but they are steadily decreasing percentage-wise (for example, see 1930-1950s in Fig. 5 where they represented most of the tools used in the past versus today). Failed eradications suggest that pest management costs and area of insecticide treated crops is likely rising over time (ca. 20% of programmes). In the case of newly established pests, the new applications of insecticides can disrupt existing integrated pest management (IPM) programmes using biological control (Cameron et al. 2009) and force the return or initial establishment of broad-spectrum insecticide programmes (Berry et al. 2009; Vereijssen et al. 2015). This pattern has been repeated many times and one of the impacts of such invasive species is to remove the future opportunity for agricultural production using organic means, where demand and opportunities do exist in Western countries.

Unexpectedly, removal by hand and host removal was the primary tool in the early 2000s. This may be due to new pests being targeted, for which there was little information on alternatives, including tree-killing beetles, such as the emerald ash borer *A. planipennis* (Fig. 5).

With the development of odour-based lures, control options for greener technologies have increased primarily for Lepidoptera, but this approach has also been used for Coleoptera and Diptera species. The SIT is a technology without non-target impacts, but the need to maintain colonies of the target pest species and security requirements for radiation sources has likely led to the limited number of lepidopteran, coleopteran and dipteran species for which SIT has been used (Klassen et al. 2021). Nevertheless, this number is gradually increasing and recent studies found that it might be feasible to tackle other pest taxa with SIT integration in the future, such as the brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae) (Welsh et al. 2017), or *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae) (Lanouette et al. 2017).

New sources of radiation that can be switched off, such as X-ray, remove the need to secure or replenish decaying radioactive sources, an expensive exercise (Mastrangelo et al. 2010; Mehta and Parker 2011). This technology is also increasingly being used for post-harvest disinfestation (Follett and Weinert 2012), but there still remain issues of reliability, which are of serious concern for the SIT component of these programmes.

The cost of achieving eradication is positively related to the size of the infested area (Fig. 6), with successful outcomes more likely when the detected population is still small and at low density, but this is not necessarily guaranteed. However, the availability of detection tools (Fig. 2) probably allows for the earlier detection of the pest, better delimitation, and thus a quicker eradication (Tobin et al. 2014).

Figure 6. Rise in normalised cost of eradication with infested area for arthropod eradication programmes where the outcome is known or unknown (USD in 2015) (from GERDA, updated from Kean et al. 2017).

3. DISCUSSION

The rapid rise in non-native arthropod incursions and eradications is a concerning trend, because it has been clear for more than 10 years that passive vectoring from international travel and trade volumes, including non-commercial postal shipments, has risen to the stage where current biosecurity processes in most jurisdictions are inadequate to prevent or even reduce incursion frequencies (Liebhold et al. 2006). This has potential implications for food production in the cases of some of the worst invaders (Vreysen et al. 2007). In part, access to nutritious food supply becomes more challenging wherever horticultural crops become scarce due to fruit fly or other insect attacks and the diet shifts towards cereals which lack some of the 20 or so micronutrients required (Broadley and White 2010). The expansion of oriental fruit fly *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae) into Africa and islands of the Pacific region, and onto additional host plants (Grové et al. 2017) illustrates the point.

On the positive side, there has been a rapid rise in government-led eradication programmes, along with a rise in countries undertaking eradication efforts (to at least 90), which is encouraging in view that in the past there was often only resignation and no attempt to contain and eliminate an incursion. GERDA does not document all of the cases where governments were quickly resigned to the inability to eradicate, but it represents cases where a positive outcome was sought in a declared eradication programme. These undeclared cases add to the increasing burden of pests discussed here, and it should be noted that the distribution of some pests have expanded well beyond what has been recorded in GERDA, due to its focus on eradication, not pest management.

A number of trends affecting the probability of success are clear in the data. The type of invasive organism makes a difference to the outcome, which is directly linked to the type of surveillance that is possible. Tobin et al. (2014) reported that the availability of lures was an enormous (>22-fold) factor increasing the likelihood of early detection followed by eradication. The type of organisms that warrant eradication are clustered in groups, which frequently turn out to be targets of pest management in other jurisdictions (Suckling 2015). This implies recognized pest status rather than new offender status, although both cases exist. Novel and unwanted tussock moths (Lepidoptera: Erebiidae: Lymantriinae) were detected in New Zealand, which led to several large-scale aerial urban biopesticide-based eradication programmes, but the particular species involved in the incursions were not anticipated (Brockerhoff et al. 2010).

The ability to conduct delimitation of an incursion is essential to the eradication success, so perhaps it is unsurprising that there is investment in developing and using insect attractants in many countries, although their commercial availability often lags behind the scientific reports (Baker et al. 2016). Across all arthropods, more than 80% of eradication programmes have been successful, although for certain groups, such as fruit flies of economic importance, the success rate is even higher (~90%). All sectors have been affected by invasive arthropods, although some have had a lot more experience than others, particularly sectors related to food production in horticulture or urban gardens, and human and animal health.

One of the species with a high colonisation rate as well as a record of eradication success is *B. dorsalis*, a tephritid fruit fly for which effective lures are available. In addition, the *Lymantria* species were well represented in this group, and they too have been eradicated many times. Attractants used to lure these two species, as well as other damaging pests, to traps have been identified as well as a number of control strategies. The advanced state of detection and control tools for *B. dorsalis* and *Lymantria* species is probably because of the large damage they cause and the rate at which they spread in the new range, which has prioritised research in this area. This has probably led to the unexpected result that a high dispersal rate is not a factor limiting success rate. As Tobin et al. (2014) highlighted, the existence of a detection tool, and thus likely a detection network programme, has had a bigger impact on success rate. Generally, the availability of multiple tools that can be used for eradications can lead to faster successful outcomes, but there are examples, such as a single or a few applications of *B. thuringiensis kurstaki* that resulted in successful eradication of *L. dispar* populations.

Tobin et al. (2014) reported 672 eradication programmes against arthropods (to 2010), and we have been able to compile additional cases, although of course current entries are best checked directly on the GERDA database, where users can find simple summary tools (Kean et al. 2017). Tobin et al. (2014) discussed several biases of data compiled in this database, e.g. more recent data are easier to locate and compile, and that successful programmes are reported more often due to the reluctance to publicize failures.

We contend, however, that the evolving database GERDA is robust to indicate the trends and drivers of eradication success and failure. For Lepidoptera other than gypsy moth, 75% of programmes were started in the last 20 years, suggesting rapid geographic range expansion under globalisation (Suckling et al. 2017). This entails that regular reviews of the trends in new data will be warranted, and/or the need of regulatory agencies to input their eradication data and use GERDA in order to remain updated. Operational biosecurity agencies involved in arthropod eradication are already invited to contribute their data to GERDA, to strengthen the evidence for conclusions and policy over time.

A fast increase in the number of eradication programmes globally suggests that current exclusion measures are not adequate to manage an increasing risk to global food security, due to an unrelenting supply of invasive species (Seebens et al. 2017). An increase in the biodiversity of invasive pests is emerging, increasing the challenge considerably. However, pest incursions have motivated the development of newer technologies that will make incursion responses and eradication success a more likely outcome in the future.

The role of public support cannot be over-stated, and as Lindeman (2013) states:

“the California Department of Food and Agriculture (CDFA) lost the battle over aerial spraying against the invasive light brown apple moth (LBAM, Epiphyas postvittana (Walker)) largely because of a report and other supporting grey literature documents that expressed highly disputable facts, evidence, and conclusions.”

Vigilance over the facts is clearly needed by the scientific community.

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