Khapra beetle, *Trogoderma granarium* interceptions and eradications in Australia and around the world

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Abstract

The number of recorded intercepts and eradications of khapra beetle (*Trogoderma granarium*) have increased in Australia and the United States in recent years. Khapra beetle is one of the most destructive stored grain pests, and infestations can destroy the quality of grain and other commodities rendering the product unfit for human consumption. This pest can be easily transported from khapra beetle countries undetected as live beetles, eggs and larvae or in a state of diapause, with the transfer of people and goods around the world. Historically, discovery of khapra beetle post-border has generally resulted in costly eradication programs including methyl bromide fumigation and years of surveillance. Misidentification, failed detection or lack of preparedness has led to slow responses and at times the wide distribution of the pest prior to action. The United States spent over thirteen years (1953 - 1966) eradicating a large scale khapra beetle outbreak that involved fumigation of over 600 sites of infestation and undertaking approximately 97,000 property inspections at a cost of USD $96 – 130 million (2016 dollars). In a first, the United States demonstrated khapra beetle was eradicable, when all infestations are detected, progressively eliminated and reinfestation's controlled. Later other infestations were detected and eradicated between 1978 and 1997, and the occasional domestic eradication program since. In this paper past khapra beetle incursions, intercepts and eradications in Australia and other countries have also been reviewed. In 2007, a post-border detection in Western Australia was eradicated. Factors contributing to the successful response strategy included the small scale infestation, limited distribution and technical feasibility of the fumigation. Prior preparedness and agreement and cooperation across government, industry and community also led to the rapid response to the incursion. The eradication programs described in this paper were found to be economically justified, although actual losses from pest damage were not that significant. For any exporting country where khapra beetle is endemic costly phytosanitary measures and trade implications come into effect. Therefore, eradication programs are worthwhile and likely to be the optimal response when costs are compared with expected damages avoided. In identifying the optimal response program an understanding of pest biology and behaviour is critical. In this paper we also compare response strategies to khapra beetle infestations with the Australian outbreak of the warehouse beetle (*Trogoderma variabile*) in 1977 – 1993. We explore the differences in pest characteristics that led to the successful eradication of one and not the other. Finally we consider the problems that are currently of most concern, which are the ability to eradicate khapra beetle in the absence of methyl bromide and the development of resistance to phosphine. Given the inevitability of future khapra beetle incursions, resolving these issues will be essential to maintaining global market access for grain exporting countries such as Australia, the United States and Canada.

Keywords: Biosecurity; Eradication; Khapra beetle (*Trogoderma granarium*); Warehouse beetle (*Trogoderma variabile*); Bioeconomic; Decision-making

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Summary

Review of the outcomes of past incursions can provide valuable information to improve biosecurity decision making in future incursions. In this paper we reviewed a past emergency plant pest incursion, and the management decisions made in response to the incursion. In particular, the eradication program that followed the incursion and the economic implications associated with the outcome. The case study assessed in detail was the khapra beetle (*Trogoderma granarium* Everts) post-border incursion in Western Australia in 2007. A timeline of the detection, eradication and surveillance of this pest tracks the preparedness, decision making process and response. In addition to this case study, we extended our review to include the similar but less economically significant warehouse beetle (*Trogoderma variabile*) of which many incursions and attempted eradication programs took place across Australia between 1977 and 1993. To gain a perspective on Australia's situation and response decisions we also considered khapra beetle detections, incursions and eradication programs in the United States, Japan, Korea, Africa, New Zealand and Vietnam. Examination of intercept data from the United States provides insight into the originating countries and commodities that have the potential to introduce khapra beetle, and underscores the increasing number of intercepts in passenger luggage.

In summary, the khapra beetle incursion was detected in a house in metropolitan Perth, Western Australia in 2007 and was reported to the authorities by the occupants. The house was voluntarily quarantined and fumigated, and a two year trapping program took place. Delays in response often occur whilst information about the pest is being gathered. However, this was avoided because the khapra beetle had been well documented earlier in various preparedness and contingency plans. Delays in seeking agreement across government and industry, as well as cost sharing arrangements were minimised because the pest fell under the Emergency Plant Pest Response Deed. The indicative expected cost of this eradication program was AUD $169,500 to be shared across Federal and State governments and industry at 40%, 40%, 20% shares. Actually, the program is reported to cost AUD $207,685 with only AUD $84,322 eligible for cost sharing and the remainder borne by the Department of Agriculture and Food Western Australia. The variance came from an over estimate of the fumigation cost, unexpected cleaning expenses and additional staff costs.

Had the pest established in the west, those at most risk of trade bans was Western Australia, whose wheat export value was AUD $2.7 billion in 2012-13, and approximately AUD $1.8 billion in each of the two years prior. Had trade bans been imposed Australia wide the potential loss from the market of susceptible products to non-khapra beetle countries in 2012 and 2013 was valued at approximately AUD $5.5 billion. The successful eradication of the khapra beetle has allowed Australia to maintain international trade relationships and continue trading without strict sanctions imposed or additional costly fumigation requirements.

In this review we advocate that khapra beetle is eradicable as shown by Australia, the United States, Japan and Africa. The warehouse beetle eradication attempts in Australia demonstrate how decisions evolve and response

strategies develop over time as new information about the pest, its distribution and probability of success is better understood. The spread rate of the warehouse beetle is much greater than the khapra beetle because it can fly and live outside of building structures. Furthermore, the intention, cost and priority given to an eradication program must be worthwhile with respect to the actual losses the pest or disease will cause, whether that be from product damage or trade implications. The potential damages and losses caused by the warehouse beetle are less than that of the khapra beetle and therefore a large scale effort and cost required to eradicate it is not warranted. Containment of the warehouse beetle and eradication of the khapra beetle was and is the most likely optimal strategy in the past and future.

In future, we foresee potential issues that are likely to have serious consequences in eradication response programs for emergency plant pest incursions of this type. Firstly, there is a need for preparedness of future strategies and fumigation options in the absence of methyl bromide. This is not only required because of the phase out, restriction of use or resistance to methyl bromide, but the potential for community objection, increase in public health concerns or the technical feasibility in the use of this fumigant. With a new strategy and fumigant comes the need for approval that the new treatments meet the requirements for quarantine. Other critical outstanding issues that need addressing are solutions for rapid, simple, reliable identification and improvements in detection, phytosanitary measures, traps and attractants.

It is expected that future incursion response decisions may be made with incomplete information and potentially in haste. The benefits of delay to understand what you are dealing with, by learning the pest's biological and behavioural characteristics and the distribution through delimitation could avoid costly errors in judgement. Finally, statutory support and the powers to act to enforce and implement quarantine regulations over property and business units may not have been fully tested and are open to legal hold ups and community defiance or rejection. Community support is essential when dealing with landholders, householders and property access rights. In general, this has been well received in small scale response programs in the past. However, gaining community support could be more difficult in a large scale response such as in metropolitan areas, the evacuation of towns, or the heavy use of dangerous or environmentally damaging fumigants such as methyl bromide. Furthermore, the reliance solely on government departments to detect and perform the response, eradication and surveillance is fraught with failure. The protection, management and mitigation benefits generated from awareness campaigns and education programs would outweigh any reasonable costs associated with these activities.

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1. Introduction

As a consequence of global trade and rapid transfer from one region, state, Province, country or continent to another is the risk of transfer of invasive alien species. Trading organisations and border control regulators monitor, conduct inspections, quarantine and at times refuse entry or departure of import and export goods to avoid the introduction of invasive alien species (IAS) to new regions. If the IAS is intercepted at the border prior to entering the importing country social, economic and environmental costs can be prevented. However, if the IAS becomes a post-border biosecurity incursion these costs can run into millions of dollars for many years to come. Often additional resources are deployed to strategically manage and respond to the border breach for programs such as eradication, containment and surveillance which can run for several years. Australia for example has responded to a number of emergency plant pest post-border incursions such as the Russian wheat aphid (*Diuraphis noxia* (Mordovilko)) in 2016, banana freckle (*Phyllosticta cavendishii*) since 2013, citrus canker (*Xanthomonas citri* subsp. *citri*) 2004 – 2009, red imported fire ants (*Solenopsis invicta*) since 2001 and the khapra beetle (*Trogoderma granarium* Everts) in 2007 and again in 2016 (DAWR, 2016a).

Khapra beetle is amongst the most economically damaging stored grain pests. This pest is thought to have originated on the Indian subcontinent and has spread to other countries with the movement of people and goods to form viable populations. Khapra beetle prefer hot arid climates or hot dry conditions in stored commodities (Rees and Banks, 1999). It infests an extensive range of stored commodities such as food products, grains, cereals and spices. In suitable conditions and with access to a source of food, reproduction occurs almost immediately and populations can grow rapidly. Feeding causes damage and contamination of the product. The presence of khapra beetle in food products can render it unfit for human consumption because of contamination from the cast larval skins during the five developmental moults, larvae hairs, excreta and dead adults. Strict quarantine regulations are in place throughout the world to avoid importation of the khapra beetle, and countries with established populations face export restrictions and regulation.

Detection and control of khapra beetle in the movement of cargo around the world can be difficult. There are four life stages of the khapra beetle, egg, larva, pupa and adult. As an adult, males live for 7 – 12 days; a mated female 4 – 7 days and an unmated female can live up to 20 – 30 days (Rees and Banks, 1999). If the female is mated only once she will lay about 60 eggs, but if mated a second time then up to 500 eggs can be laid. However, on average 50 – 90 eggs are laid since fecundity is reduced by up to 25% if there is a delay between mating dates of 15 – 20 days. Also, if intermittent starvation, dormancy and feeding have taken place up to 60% less eggs are produced. Khapra beetle has survived several hours at 60°C and -15°C for short periods, but optimum conditions for development are 33 - 37°C with 45 - 75% r.h (Rees and Banks, 1999). The upper limit is about 46°C, and at 70% r.h. the lower limit is about 22°C if development is to occur. In unfavourable conditions such as unsuitable climate or crowding the larvae can enter diapause. This can extend up to six years and halts growth, moulting and maturity until suitable conditions and food source are available. The effectiveness of chemical control whilst in a diapause state is lessened. Whether active or in diapause the khapra beetle may hide in cracks and crevices of packaging, shipping containers and warehouses.

There are many treatment and control methods for khapra beetle. For example, fumigants such as methyl bromide and phosphine; controlled atmospheres such as carbon dioxide based or low-oxygen; heat treatment; and irradiation (Rees and Banks, 1999). Each has a varying degree of success and challenges associated. Methyl bromide remains the fumigant of choice, although there are records of a high tolerance to the fumigant, particularly when the pest is in diapause. Methyl bromide also faces usage restrictions because it is an ozone depleting substance listed for future phase out under the Montreal Protocol (Porter et al., 2009). An alternate reasonably effective fumigant is phosphine. However, concerns about the misuse and development of resistance, its penetration of some materials, the long exposure time required and poor efficacy below 15°C has resulted in Australian Quarantine and Inspection Service (AQIS) not approving it as a quarantine treatment against khapra beetle (DA, 2015a; Rees and Banks, 1999). In the absence of a suitable alternative for methyl bromide an international exemption on the phase out for quarantine purposes is in place (DA, 2015b).

In line with many other countries, the Australian quarantine authorities have intercepted khapra beetle at borders periodically. Worldwide the *Trogoderma* genus has approximately 130 described species of which at least 52 species are endemic to Australia (Castalanelli et al., 2012). Durrant (1921 in Lindgren, Vincent, and Krohne 1955) reported that khapra beetle larval remains were found in wheat samples from Queensland (Qld). However, there was uncertainty as to whether it was the ship that was infested in India before arriving in Australia or was infested by a Qld population (Ward, 1965). Confusion and misidentification of a non-pest undescribed native *Trogoderma* beetle in the late 1940s led to Australia being declared as a 'Khapra beetle country' (Emery *et al.* 2008). Trade issues related to this status took over 15 years to rectify and prove that Australia is free of khapra beetle (Butcher, 1994; Emery et al., 2008). There are more than 70 countries known to be infested with khapra beetle throughout Asia, the Middle East, Africa and Europe (DAWR, 2016b). Australia responded to a post-border incursion in Western Australia in 2007 and recently in South Australia in 2016, and currently assumed to be free of khapra beetle.

The post-border incursion of khapra beetle to Western Australia in 2007 and the emergency response that followed has been analysed in detail to examine the decisions made, economic impact and the determinants of a successful eradication. In contrast, we investigated the incursions and unsuccessful containment and eradication programs that occurred across Australia between 1977 and 1993 for the similar, but much less significant warehouse beetle (*Trogoderma variabile*). To gain perspective of the ongoing threat of khapra beetle breaching borders included is a summary of past incursion responses and intercepts from the United States, Japan, Korea, Africa, New Zealand and Vietnam.

This paper is organised as follows. First we review the khapra beetle incursion and successful eradication in Western Australia in 2007 in detail, and current knowledge about the recent South Australian incursion and eradication. Second, we draw a parallel with the eradication strategies and decisions made in the earlier warehouse beetle incursions in Australia. Thirdly, report on the detection and eradication programs for khapra beetle in the United States and other countries. Fourth examine the limited use and future of methyl bromide and alternate options for control of khapra beetle. Lastly, we analyse the economic risk and implications of future incursions and likely costs associated if khapra beetle were to become established in Australia.

2. Khapra beetle reaches Australia

2.1. Western Australia: detection and eradication in 2007

In April 2007, a post-border detection of khapra beetle was identified in a house in Perth, Western Australia (WA) after the infestation was discovered and reported by the occupants. Live insects were detected in the house by a recently arrived migrant family two weeks or so after the delivery of their personal effects. With the unpacking of their belongings the infestation had been spread throughout the two-storey house. This prompted a call to a local pest controller, who fortunately recognised the khapra beetle from an extension program administered by the Department of Agriculture and Food Western Australia (DAFWA) (Emery *et al*. 2010). The extension program had aimed to upskill local pest controllers in their ability to recognise introduced pests, and report their findings to the appropriate authorities. A biosecurity officer was sent to the residence the same day to collect larvae and adult beetle specimens, which were positively identified as khapra beetle the following day by a DAFWA taxonomist. Another opinion was sought from a Commonwealth Scientific and Industrial Research Organisation (CSIRO) taxonomist who confirmed the post-border detection of khapra beetle a week later (Emery *et al*. 2010).

Subsequent examinations of five surrounding residences revealed that the infestation was contained to the single dwelling. The khapra beetle cannot fly and natural spread is limited, long distance dispersal occurs primarily through human activity. The risk of spread from this site was considered low because of the pest's mode of dispersal, movement restrictions of goods from the property and the plan to apply chemical treatments in and around the property without delay. The location of the incursion and distance to the nearest grain handling facility (Forrestfield 22 kms) and grain export terminal (Kwinana 40 kms) also supported this judgement (Emery et al., 2008). As an interim measure steps to minimise spread began within 24 hours of discovery. Pesticide treatments were applied inside and outside of the house. The Co-operative Bulk Handling Group (CBH) was engaged not only due to their stakeholder interest in the grains industry, but also for their expertise in grain pest control and fumigation. Inside the house, a fogging treatment of permethrin was applied to clothing and personal effects, and a more persistent pyrethroid, bifenthrin was applied as a barrier treatment to the outside of the house (DAFWA, 2007a). The family car was also treated and parked off the property. When insect activity was sighted inside the cardboard lining of packing boxes in the garage an additional fumigation was carried out by CBH. These boxes were loaded into an enclosed fumigation trailer and both the trailer and garage were sprayed with Pestigas (DAFWA, 2007a). Other personal items in the garage were placed in quarantine plastic bags, sprayed with Pestigas, sealed and left in the garage until the next house fumigation when the bags would be re-opened. All packing boxes in the fumigation trailer were fumigated again at the DAFWA facility and destroyed or buried (DAFWA, 2007b; Emery et al., 2008).

Containment of the pest to one dwelling suggested to DAFWA experts and the Consultative Committee on Emergency Plant Pests (CCEPP) that eradication was technically and economically feasible (DAFWA, 2007a). It was also agreed that khapra beetle is a Category 2 pest and that the incident was to follow the Emergency Plant Pest Response Deed (EPPRD) and PLANTPLAN process (DAFWA, 2009). DAFWA prepared the draft Emergency Plant Pest Response Plan (Emergency Response Plan) and within 10 days of taxonomic identification of the pest the CCEPP had endorsed the plan (DAFWA, 2009). The swiftness of preparing the draft Emergency Plant Pest Response Plan can be partly attributed to the previous work by Rees and Banks (1999); Botha *et al*. (2005); and McElwee (2000a; 2000b). The availability of key information documented about the pest itself, control methods and potential economic impact avoided unnecessary delays and assisted in the successful eradication response. A Scientific Advisory Panel (SAP) was formed upon the request of the CCEPP to consider the trapping and monitoring requirements for WA and any trace forward sites. Recommendations made by the SAP were added to the final Response Plan and included details of the post-treatment spraying, monitoring and trapping activities and locations, as well as the equipment to be used (DAFWA, 2007a). An indicative cost for eradication and a two year trapping and monitoring program was estimated to cost AUD $169,500. Under the EPPRD the estimated AUD $169,500 to implement the eradication and surveillance response plan was eligible for the pre-existing cost sharing arrangement of the Deed (DAFWA, 2009). The contribution share of costs between the Australian and State/Territory Governments and the rice and grains industry for a Category 2 pest is 40, 40 and 20 percent respectively (PHA and DLA Piper, 2014).

The house was sealed in plastic wrap and fumigated with methyl bromide. Methyl bromide is the preferred fumigant for quarantine treatment against khapra beetle worldwide (DA, 2015b; DAFWA, 2007a; Rees and Banks, 1999). The house was vacated for a period of time under voluntary quarantine during the methyl bromide fumigation procedure and the residents left with minimal, but treated items (DAFWA, 2007b). Officers from the Pesticide Safety Branch (Department of Health Western Australia) inspected the property and set conditions for the fumigation to proceed (DoH, 2007). As a precautionary measure the occupants of the five immediate neighbouring properties were also temporarily relocated with accommodation expenses covered. The neighbours were evacuated for about 3 – 4 days until the treatment was completed and the infested property cleared of fumigant (DAFWA, 2007b). The evacuation period of the infested house extended much longer than expected due to unforeseen circumstances.

Fumigation was carried out by CBH's contractor on a cost recovery basis in the interest of protecting the grain industry (DAFWA, 2007a). The house was covered in shrink wrapped plastic sheeting of industrial grade 200 μ low density polyethylene, Figure 1. This method surpasses previous techniques such as tarpaulins or canvasses with a tighter fit around the structure, reduced leakage, safer to handle in windy conditions and is easier to secure and seal (DAFWA, 2007a). Preparation and equipment for the fumigation consisted of three gas introduction points into the house; four electric fans used for circulation; six gas monitoring points; and one temperature probe to inject and monitor the gas concentration (Emery et al., 2010). The number of gas introduction points and fans were later deemed excessive and unnecessary. Only one primary upstairs roof space gas line was used and rapid even gas dispersal throughout the house and adjoining garage occurred (Emery et al., 2010). The methyl bromide fumigation rate was to be at an internationally established rate known to control khapra beetle (AQIS T9056). The best control option described by Dillon (1968) cited in the Threat-Specific Contingency Plan 2005 for khapra beetle (Botha et al., 2005) is fumigation with methyl bromide as a hot gas injected from several points into the building and diverted within the structure at a rate of 24 g/m^3. The current recommended dosage rates for methyl bromide fumigation for the control of khapra beetle is 80 g/m^3 for 48 hours with minimum concentration of 24 g/m^3 after 24 hours at normal atmospheric pressure and must account for the ambient temperature within the fumigation enclosure (DA, 2015b). The planned fumigation for this incursion was for methyl bromide to be injected at 80 g/m^3 for 48 hours at 21°C at normal atmospheric pressure with an end point concentration of 20 g/m^3 (Emery *et al*. 2010). Within two hours after introducing 100 kg of methyl bromide five monitoring points had reached the maximum concentration readable by The Drager® tubes of 80 g/m^3 and the sixth was at 68 g/m^3. The readings remained at the maximum possible measure of 80 g/m^3 up to the 8th hour, which impacted on the average over the 48 hour period. The average concentration recorded was 39.8 g/m^3 which is likely to be incorrect due to the measuring limitations reached early on (Emery *et al*. 2010).

Figure 1. Khapra beetle infested house in Western Australia covered in shrink wrapped plastic sheeting in preparation for methyl bromide fumigation. Source: Under Raps Pty Ltd, n.d.

Prior to the property being re-occupied tests were conducted to confirm the site and receptacles had less than 5 ppm methyl bromide remaining (DAFWA, 2007b). Air quality assessments by the ChemCentre of Western Australia identified a number of compounds present such as methyl bromide, dimethyldisulphide, toluene, ethylacetate and methyl isobutylketone. A post fumigation odour extended the residents' relocation period from two days to seven weeks (DAFWA, 2009). The odour resembled that of a decaying body which attracted flies to the site. Components attributing to the smell were sulphide, butylketone and dimethyldisulphide likely to result from the reaction with sulphur in the carpet underlay (Emery et al., 2008). Two days of aeration with ozone fans, steam cleaning carpets and ventilation was not sufficient to remove the smell. Finally, carpets and underlay were replaced. Although methyl bromide is a gas and not known to leave residue, additional soft furnishing items were also replaced as requested by the occupants. The current Australian Fumigation Accreditation Scheme (AFAS) Methyl Bromide Fumigation Standard (DA, 2015b) lists commodities for which problems may occur when fumigated with methyl bromide, these include woollens, rubber goods, rug padding and viscose rayon. This information may not have been available at the time of fumigation and has since become known. Once the odour had dissipated, further air quality tests were conducted and a forensic cleaning company thoroughly cleaned the house with alcohol-based products and odour eliminator (Emery et al., 2008). The additional costs from this unexpected event were equivalent to the actual fumigation cost. In hindsight, forensic cleaners, Ozone treatment and carpet replacement would be a priority rather than steam cleaning and ventilation (DAFWA, 2009). Better preparedness of furniture, fittings and chattels prior to fumigation would be considered in the future. Also, the estimated evacuation period was rather optimistic given the unexpected delays (DAFWA, 2009).

The source of the khapra beetle was never established, but it is suspected that the khapra beetle was in the shipping container carrying the migrant family's belongings from the United Kingdom (DAFWA, 2009). Furthermore, a food source such as a wheat heat bag may have been present during the journey and hold up period which could have sustained life and population development of the short-lived insect (Emery et al., 2008). Tracing investigations of the shipping container and its contents forward and backward identified potential pick up points and locations the pest may have been transferred from and to. The incoming shipping container had passed through many ports leading up to its arrival in Fremantle, Western Australia and had contained suitable host material at times. Its most recent pathway, in order included Thailand, Germany, South Korea, Malaysia, Pakistan, Oman, England, Scotland, Netherlands, Germany, Singapore and finally Australia (DAFWA, 2009, 2007b). It was known at the time from Rees and Banks (1999) that khapra beetle was established in South Korea, Malaysia, Pakistan, as well as many parts of the Middle East and present in the United Kingdom. There was uncertainty about Thailand, Germany and Singapore. Khapra beetle has now been recorded as eradicated from Germany and Malaysia, formerly present but now absent from Netherlands and England, present in South Korea, Pakistan and Oman and unreliably recorded as absent from Thailand (CABI, 2013; DAWR, 2016b). Prior shipment cargo contents had included cotton textiles, iron and steel articles, chemical products and foodstuffs. Therefore, the source could have been from any number of locations or host material. International marine shipping is known to be the source of translocating many invasive species. Paini & Yemshanov (2012) analysed and modelled Australia's risk of a khapra beetle incursion arriving via a shipping network. Modelled simulations identified the countries that are the most likely source of an introduction to Australia as Taiwan, Republic of Korea and Egypt. The infested container on this occasion passed through two Korean ports, one of which was Busan which was ranked as the most likely source of the introduction of khapra beetle for the Fremantle port. However, the Australian ports with the greatest potential of receiving khapra beetle infested cargo were identified as the ports of Melbourne, Botany Bay and Brisbane.

After the six week voyage to Australia and inspection of the shipped contents by the Australian Quarantine and Inspection Service (AQIS) in WA no pests or reason for further quarantine measures had been detected. The family's personal effects were then transferred to another shipping container temporarily and held at the storage facility until delivery. The likelihood of a pest entering Australia and reaching agricultural regions is often fiercely debated. This khapra beetle incursion draws attention to the closeness of a shipping container storage facility to the Metro Grain Centre (MGC) located in Forrestfield. The Euclidean distance is approximately 1 km between the container storage facility and the MGC which can store over 200,000 tonnes of grain at capacity (CBH Group, 2014). The original shipping container bringing in the shipment departed for Norway prior to the detection of the pest. AQIS officials intercepted the container on arrival in Norway, but there was no sign of khapra beetle or food residues (Emery et al., 2008). In Western Australia, AQIS also inspected a consignment that was situated directly adjacent to the infested shipping container at the storage facility, it too was found to be insect free (DAFWA, 2007b). The second container used for temporary storage had been used for two new consignments to Queensland on the east coast of Australia prior to the detection. This container departed Fremantle with consignments of personal effects and docked in Brisbane where another consignment was added and shipped on to Cairns in far north Queensland. The Brisbane added consignment was delivered directly to a residential property in Cairns, and the two Western Australian consignments remained in the container at the depot and until delivered to a house in Gordonvale.

The SAP recommended that the three shipping container storage facility warehouses in both WA and Qld have a crack and crevice spray treatment. The two houses that received the consignments in Cairns and Gordonvale in Qld also received bifenthrin and permethrin insecticide treatments inside and outside respectively. Recommendations given by entomologists in the United States (U.S.) was influential in the SAP deciding on the best traps to be used to attract larval and non-flying adult khapra beetles, particularly during cold weather (DAFWA, 2007a). The CCEPP supported the SAP's preference to use STORGARD® Trécé traps imported from the U.S. These traps are known for providing an early-warning detection and being sensitive to low populations (Trécé Inc., 2013). To attract adult khapra beetles the traps were baited with kairomone lure strips, a species-specific pheromone, and ground raw wheat germ for the larvae (Emery et al., 2008). Sites identified for the trapping and monitoring program were the fumigated house and five neighbouring houses, two recycling and refuse facilities in WA, two shipping container storage facilities and the two houses in far north Qld. An intense trapping and inspection program was run for two years in WA from June 2007 to May 2009. This included two summer seasons when the pest is most likely to be active and detected if present. Queensland's less intensive program ran for six months with a single trap in each house and six at the Cairns storage facility. In total there were 1,273 trap inspections in WA and 34 in Qld. The inspections were weekly initially, later extending to monthly. Personal Digital Assistant (PDA) technology and software was utilised during the two year period recording GPS locations, navigation itineraries, date/time stamps and site imagery to demonstrate pest freedom with robust surveillance data (Emery et al., 2010). Over 180 specimens were found in the traps, of which 43 were Dermestidae, but further taxonomic identification revealed that none of these were khapra beetle. As a part of a National Trapping Programme for *Trogoderma* and related Dermestids, pheromone and/or food lure baited traps were placed across major grain production and handling regions of Australia between October 2009 and October 2011 at 91 sites (Cunningham, 2012). From the 1,196 traps returned to DAFWA, 9,435 putative Dermestid specimens were received, of which 2,773 specimens were formally identified to the genus or species level and the remainder sorted to morphospecies. No khapra beetle was found, supporting Australia's status of being a non-khapra beetle country.

The expected cost of a proposed response is often an underestimate of the true cost of the response with unexpected circumstances and additional resources adding to the initial estimates. This can also impact on cost sharing arrangements between governments and industry. For this response only AUD $84,322 of the estimated AUD $169,500 was shared between government and industry. An additional AUD $123,363 was primarily staff resourcing costs that had not been accounted for in the proposed response plan. Resourcing became an issue when it was difficult to employ casuals, trap inspections had to be carried out after hours, and activities in addition to everyday duties were imposed on existing staff (DAFWA, 2009). This revealed the conflict between business as usual everyday duties and emergency response priorities. Suitably trained staff were needed for the emergency response and temporarily vacant positions. As a result, these additional costs incurred were covered by DAFWA in kind. The actual cost share contribution between the Australian and State/Territory Governments and the rice and grains industry for this incursion response was 16, 16 and 8 percent respectively, and the additional 60% covered by the WA Government. However, the cost share contribution for the eligible costs (AUD $84,322) remained at 40, 40 and 20 percent (Table 1).

Table 1. Actual cost and contribution share of the Australian and State Governments and the rice and grains industry for the eradication of khapra beetle in WA 2007 – 2009. Source: DAFWA 2009

Contributor	**Eligible cost** (AUD $)	**Share** (%)	**Share** (AUD $)	**Additional non-share cost** (AUD $)	**Total cost** (AUD $)	**Total share** (%)
Australian Government	84,322	40	33,729	0	33,729	16
State/Territory Governments	84,322	40	33,729	0	33,729	16
Industry	84,322	20	16,864	0	16,864	8
DAFWA	-	-	-	123,363	123,363	60
				Total	**207,685**	**100**

The Australian Bureau of Agricultural and Resource Economics (ABARE) prepared a Cost-Benefit Analysis and economic assessment for inclusion in the Emergency Response Plan, which also supported the eradication response. The gross value of susceptible agricultural production to khapra beetle infestations post-harvest in 2005-06 was AUD $9.6 billion and the export value of susceptible plant products was AUD $5.8 billion (DAFWA, 2007a). In volume terms, WA had accounted for over a third of all wheat production and a quarter of all barley production that year (ABARE, 2007a). The estimated cost of eradication was less than 0.1% of the value of susceptible commodities exported in 2005-06 and a successful eradication was expected to have substantial net economic benefits (ABARE, 2007a). Furthermore, the costs from the establishment of a khapra beetle infestation in Australia was expected to come in the form of lost export markets, reduced marketability, reduced prices due to quality degradation and consumer safety concerns (ABARE, 2007a, 2007b). Australia's key wheat trading partners without khapra beetle, such as Indonesia and Japan, could be expected to impose bans on imports or impose sanitary restrictions such as fumigation if the pest were to become established in Australia (ABARE, 2007b). No trade restrictions were imposed as a result of this incursion or during the eradication and surveillance period (DAFWA, 2009).

Previous economic analyses by McElwee (2000a, 2000b) investigated reasons for targeted surveillance for khapra beetle and the potential impact of khapra beetle on the WA wheat industry. The benefit of surveillance was expected to come from early detection and the gain that may follow, such as the reduction in emergency response costs, reduction in trade disruption and long term savings from eradication rather than containment or control. Surveillance was deemed economic if the probability of an incursion is high or eradication costs are likely to be high. Key factors identified for the economics of surveillance by McElwee (2000a) were the:

i) cost of surveillance;
ii) probability (or expected frequency) of an incursion;
iii) proportion of incursions detected by the surveillance program and not by other means, eg. reported by the public;
iv) expected reduction in emergency response costs as a result of early detection by surveillance; and
v) change in the probability of a successful emergency response as a result of early detection by surveillance.

However, the economic viability of targeted surveillance is subject to changes in quarantine procedures. Improvement in quarantine detections is likely to reduce the number of incursions, hence the number of surveillance detections, and therefore be a substitute and reduce the benefit of surveillance. Alternatively, improved quarantine could complement targeted surveillance and in combination be the optimal allocation (McElwee, 2000a).

McElwee (2000b) assessed the potential impact an established khapra beetle population may have to the wheat industry in WA. He assumed that 1% of stored grain would be affected in the first year of establishment and spread to 90% of its potential distribution was estimated to take 20 years. The spread rate was based on predictions made about the dispersal of a similar pest, the warehouse beetle. Negligible losses of stored grain were expected due to effective pest control methods in use using phosphine. Uncertain factors likely to impact on the cost of population establishment were excluded. For example, the effectiveness of phosphine on resistant strains from Africa and the Indian subcontinent, and the lack of approval from AQIS and other trading countries of the use of phosphine as a fumigant for khapra beetle. The assessment therefore focussed on trade impact imposed by importing countries under four scenarios described as follows:

1. Non-khapra beetle countries demand all shipments come from areas free from khapra beetle.
2. Same as scenario 1, but include countries of uncertain status such as Indonesia, South Korea and Japan as non-khapra beetle destinations.
3. Non-khapra beetle countries cease accepting wheat from the state of WA.
4. Same as scenario 3, but include countries of uncertain status such as Indonesia, South Korea and Japan as non-khapra beetle destinations.

A 20% price penalty was applied to wheat that could not be sold to its usual destination in each scenario. This is indicative of a downgrade from Australian Standard White (ASW) wheat to domestic feed wheat. The status of countries with and without khapra beetle and their standpoint on the seriousness of the quarantine pest was assumed to remain constant over time. Annual cost to the wheat industry was estimated between AUD $46 million - $117 million. Present value over 30 years with a 7% discount rate ranged from AUD $201 million to $1.6 billion as shown in Table 2.

Table 2. Estimated cost to the Western Australian wheat industry if khapra beetle were to establish. Four market scenarios were tested that included a price penalty and accounted for spread over 20 years.
Source: McElwee, 2000b

Scenario	Annual cost in first year of incursion (AUD $m)	Annual cost when spread complete (AUD $m)	Present value of costs over 30 years at 7% disc. rate (AUD $m)
1	0.46	46	201
2	1.2	117	517
3	46	46	610
4	117	117	1,571

More recently Cook (2015) estimated the likely impact that can be expected if khapra beetle became established in WA. If the incursion occurred in year one khapra beetle ranked seventh of ten pests and diseases threatening the WA grains industry based on the annualised average damage costs. These costs included direct and indirect losses over time as well as response expenses and averaged AUD $46.1 million. The costs were then estimated with a random incursion frequency based on a uniform probability distribution. Likelihood of arrival and establishment over a 30 year period ranged from quarterly to one in every fourteen years. Khapra beetle was now ranked fourth with an average cost of AUD $0.9 million. The direct losses to grain in infested storage facilities were estimated at 5 – 20%, and export losses at 10 – 20%.

Success of the eradication program can be attributed to the speedy decision and response to the post-border incursion. This can be partially credited to the availability of information at the time of the incursion from other eradication programs such as those in the United States and the warehouse beetle in Australia. Costs associated with the preparedness documents by Rees & Banks (1999) and Botha (n.d.) is unknown, but the benefit is obvious particularly in terms of timeliness and accessibility to information when developing the Emergency Response Plan. In the Appendix, Figure 5a - h depict a concise timeline summary of the series of events, critical, and key stages as well as missed opportunities or unexpected incidences that occurred. The timelines display periods of Preparedness prior to the incursion and each of the PLANTPLAN phases including Investigation, Alert, Operational and Stand down, and it finishes with post-incursion and post-eradication activities. This incursion response has demonstrated the efficiencies that can be gained in an emergency when information is known, agreements are in place, and when resources and experts are available. Had the eradication of the pest not been successful, the potential severity of the implications could be significant. Previous experience in the U.S. with khapra beetle proved eradication was possible (Section 4). However, the warehouse beetle incursions in Australia had showed how a *Trogoderma* grain pest species could spread rapidly to reach an uncontrollable distribution level (Section 3). Fortunately, the khapra beetle incursion eradication in Western Australia in 2007 was successful and the two year trapping program that followed failed to capture any of the life stages of khapra beetle.

2.2. South Australia: Detection and eradication in 2016

In May 2016, a post-border detection of khapra beetle was identified in two premises in Adelaide and one premise on Kangaroo Island, South Australia (SA). Early indications about the incursion source of the larvae and adult khapra beetles trace back to a contaminated sea container with a consignment of imported plastic food grade containers (DAWR, 2016c). On the 20th of May 2016, the National Management Group met to endorse the recommendations made by the CCEPP for the *National Khapra Beetle (Trogoderma granarium) Response Plan* (DAWR, 2016c). Surveillance and control response measures were conducted by the Department of Primary Industries and Regions South Australia (PIRSA), including eradication. It was announced on the 24th of May 2016 the pest had been contained and destroyed, and authorities were confident the khapra beetle had not spread beyond these three premises (DAWR, 2016d). Precautionary trapping and monitoring surveillance, as well as tracing activities were continuing at the date of this paper.

3. Warehouse beetle: Control and surveillance programs in Australia 1977 – 2003

Khapra beetle and the warehouse beetle (*Trogoderma variabile)* species are from the same family and there are similarities between the WA khapra beetle incursion and the warehouse beetle incursion that occurred in the late 1970s in WA. A warehouse beetle infestation was discovered at a farm in Morawa 400 km north of Perth WA in 1979 and an isolated eradication took place. This came after the detection in the Rice Grower's Co-operative mill at Griffith New South Wales (NSW) in March 1977 (Butcher, 1994; Emery et al., 1998). A survey of the surrounding areas of the first infestation in NSW found the pest in three more rice mills located at Leeton, Coleambally and Deniliquin, two farms at Griffith and a farm at Yanco (Emery et al., 1998). A three year eradication program was approved at an estimated cost of AUD $610,000. The eradication began almost immediately by cleaning storages, fumigating produce and spraying premises (Emery et al., 1998). However, by mid-1980 it became apparent the pest was far more widespread than initially thought. It was now present at commercial and industrial premises, farms and throughout the rice industry. A further AUD $404,000 was contributed by the State and Australian Governments when the pest was found further afield in the northern areas of NSW by 1981 (Hartley and Greening, cited in Emery et al. 1998). The widespread distribution led to the abandonment of the eradication program in NSW in 1981/82 (Butcher, 1994; Emery et al., 1998).

WA's warehouse beetle infestation in 1979 was believed to be an isolated case, therefore the eradication effort continued in the west. Although, the infestation was thought to have been eradicated, a second eradication program began at the same property when it was found to be reinfested in 1991. At a cost recovery basis of AUD $50,000, methyl bromide and phosphine were used in the sheet fumigation of the many structures on the farm, and a survey of surrounding properties within 30 km was conducted (Butcher, 1994). Resources were provided by the state Agriculture Department, a bulk grain handler and the local shire council (Emery et al., 1998). With no further detections discovered, eradication was deemed successful. A trapping program began from spring of 1991 until 1992. Pheromone traps were placed at likely warehouse beetle locations throughout the wheatbelt and Perth metropolitan areas (Butcher, 1994). Within months another infestation was located 150 km away at a grain-producing property at Pithara in WA (Butcher, 1994). It is noted that another source named Three Springs as the next detection site (Emery et al., 1998). This time the Australian Protection Board of Western Australia (APB) decided to opt for containment with residual insecticides and fumigants, while a more intensive state trapping and detection program ran for approximately nine months to delimit the pest's distribution. Pheromone-baited flight traps were considered the more cost effective and reliable option rather than physical inspections at suspect premises (Butcher, 1994). The traps were distributed throughout the state in the wheatbelt and in the Perth metropolitan area. The total emergency response cost in 1991 and 1992 was approximately AUD $443,500, and ongoing control and containment was estimated at AUD $78,000/year (McElwee, 2000a). By 1993, 641 traps were in use across the state. This came after the discovery of more infestations at the rural towns of Carnamah, Coorow, Wongan Hills, Dalwallinu and metropolitan Perth. The pest distribution broadened to include Three Springs, Williams, Goomalling, Northam, Wickepin, Clackline and Kellerberrin (Figure 2). In Three Springs and Carnamah the source of the infestation could be identified and treated. Carnamah was a major infestation site that had warehouse beetles detected in 20 houses and commercial premises, and at 23 farm houses. Spread of the pest was aided by humans and appeared to be via produce purchased from the local supermarket (Emery et al., 1998). The level of infestation at most other sites was low, and much less than the area and number of insects caught per trap in central NSW during the same period.

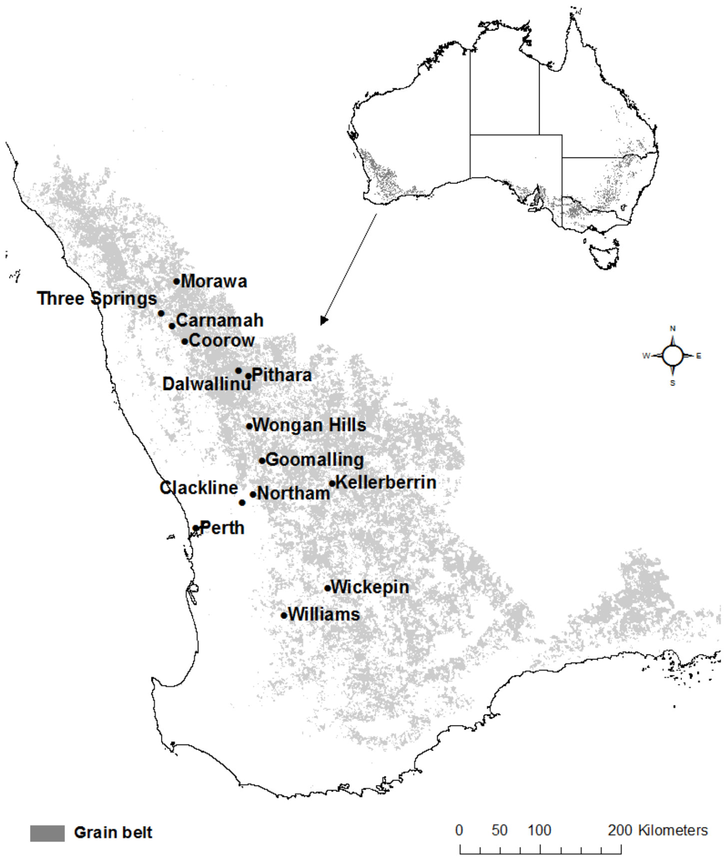

Figure 2. Locations warehouse beetle infestations were detected in Western Australia 1991 – 1993.
Sources: Butcher, 1994; Emery et al., 1998. Map author: Day, 2016

Proposals for different strategy options were considered as follows. Methyl bromide fumigation at each farm was estimated at AUD $40,000 and AUD $3,000 for each town building. Eradication was estimated to cost AUD $2 million in the first year, AUD $640,000 in the second year and approximately AUD $250,000 for every subsequent year (Butcher, 1994). In total, a program over 30 years was estimated to cost AUD $12 million, and approximately AUD $6.4 million when discounted at 7% (Butcher, 1994). A 70% chance of success was assumed and the remaining 30% was the probability that all properties would become infested. Over 30 years and including on-costs of 25% the net present value was AUD $76 million with a benefit-cost ratio of 12.83 (Butcher, 1994). Another economic assessment was conducted by Young (1994, cited in Emery *et al.* 1998) for Agriculture Western Australia. This analysis calculated the cost of a containment program over 30 years at a total cost of AUD $4.7 million, which is AUD $2.3 million when discounted to the 1994 dollar value. Under the same terms as the previous analysis the net present value for containment was AUD $16.4 million, with a benefit-cost ratio of 9.8 over 30 years. Three conditions were identified for the program to break-even (i) the number of dwellings affected is 86% less than anticipated, (ii) losses experienced by each dwelling type is reduced by 87%, and (iii) this action delays spread by 6 months instead of 5 years (Emery et al., 1998).

The magnitude of the eradication effort required was insurmountable and the likelihood of success unclear with recurring reinfestation a real threat. An eradication program would have imposed unforeseen and potentially unmanageable costs to individual landholders. Funding assistance or compensation for damages from government or industry would have been needed (Butcher, 1994). Fumigation of every building was a likely prospect, and uncertainty existed about the presence of warehouse beetle outside of buildings. As an example, the Carnamah had a population of about 600 with 200 buildings, all of which would need evacuating to ensure safe and effective fumigation of all town site structures (Butcher, 1994). Ideally, fumigation would take place in winter when adults are less likely to be in flight and reinfest, but winter conditions in WA are not conducive to fumigation treatments. Confidence was also lacking in the ability and resources available to locate all infestations and sources of infestation. Furthermore, there was an ever increasing risk of more incursions from the eastern states due to the widespread distribution of the pest in all other states except Tasmania. In April 1993, it was decided to recommend the adoption of a control and containment policy (Emery et al., 1998). Knowing the extent of the spread of the pest was influential in the decision to abandon any further eradication effort and adopt a containment and monitoring program. Surveys conducted in all mainland states in 2001 – 2002 and 2002 – 2003 seasons detected warehouse beetle at 66 of the 154 sites across Australia. These trap sites were mostly close to bulk-handling grain storage facilities. The Eyre Peninsula in South Australia was the only discrete grain handling system that was found to be free of the pest (Rees et al., 2003). Castalanelli *et al.* (2011) discovered later with DNA sequencing that 53% of the specimens collected during the 2001 – 2003 surveys were actually incorrectly identified as warehouse beetle.

Uncertainty remains about whether there were multiple incursion events of warehouse beetle to Australia. Nevertheless, the dispersal across Australia was most likely aided by humans, particularly over long distances such as between the eastern and western states (Campbell and Mullen, 2004; Castalanelli, 2011; Castalanelli et al., 2011). Campbell and Mullen (2004) investigated the spatial distribution and dispersal behaviour of warehouse beetle inside and outside of a food processing plant in the U.S. They used Trécé Inc. Pherocon II pheromone traps inside the plant that were intended to attract only males and capture or mark flying insects such as *Trogoderma* species. Outside, Scentry Biologicals Inc. Delta traps were used with the same pheromone lures. More warehouse beetles were captured outside than inside, but this may have been due to the difference in traps and placement, environmental and landscape conditions or a higher density of insects in flight outside (Campbell and Mullen, 2004). The recapture distance ranged from 21 m to 508 m with the average being 75 m. However, this measurement was not the total distance that may have been travelled between traps (Campbell and Mullen, 2004). Results also suggested that migration from outside the facility to the inside was occurring. Implications for pest management programs are (i) outside monitoring traps may give false signals for the timing or effectiveness of treatments required inside; (ii) dispersal differences between sexes should be understood when single sex pheromone traps are in use; (iii) when using inside and outside traps an understanding of the migration patterns is an important factor (Campbell and Mullen, 2004).

Misidentification can produce incorrect estimates about the population, spread, cost and the probability of success which can have severe consequences on the decision to control and contain or attempt eradication. Warehouse beetle is now a well-established pest and persistent at grain storage and handling facilities throughout Australia. It has more recently become an increasing nuisance in bulk-stored canola in southern NSW and is difficult to control in this commodity. Whilst the use of phosphine and pyrethrin may be effective for warehouse beetle, residual protectant insecticide options for use on stored canola are limited. Concerns now exist about how the establishment of the warehouse beetle may lead to complacency and misidentification of khapra beetle if it re-enters Australia. In areas with high populations of warehouse beetle it may be beneficial to introduce a community-based control and containment program. This would educate households about warehouse beetle identification and control methods. Eradication in grain storage facilities may be re-evaluated if an effective fumigant becomes available for canola.

4. Khapra beetle: Detection, eradication and intercepts in North America 1946 - 2016

The United States has thirteen of the world's *Trogoderma* species, but no established population of khapra beetle. They have had many post-border khapra beetle incursions, and have consistently intercepted khapra beetle at borders over the years, however remains as a non-khapra beetle country. The U.S. has responded to large khapra beetle outbreaks with costly eradications. The first introduction may have been to Fresno, California in 1946 where it was misidentified as the black carpet beetle (*Attagenues piceus*) and disregarded. It was not positively identified until it was found established in two wheat and barley stores in Tulare County, California in October 1953 (Lindgren et al., 1955). In early spring of 1954, the infested stores were emptied and as each load was removed it was fumigated with methyl bromide. Of the 3,700 tonne grain mass originally stored, 20% of the weight was lost from the larval feeding. At a cost of approximately USD $5,000 - $8,000 the store applied a range of control measures until no live insects could be found (Armitage, 1958, 1956). In the following year the store was used for grain, and it became heavily infested indicating that previous measures had not penetrated all possible crevices and had not eliminated all insect stages (Armitage, 1956).

Had the specimen been identified earlier, the problem may not have been as widespread as it was found to be (Armitage, 1956). In the 1950s and early 1960s khapra beetle was found to have spread into California, Arizona, New Mexico and far-west of Texas. It was found in large warehouse storage and cereal processing plants that had extensive distribution channels and at private properties in on-farm storage units (Armitage, 1956). Initially eradication was considered impossible due to the wide-ranging dispersal of the pest (Armitage, 1958). The only conceivable immediate action was to advise grain and seed handlers of the significance of the pest and carry out precautions to minimise spread and control infestations at low levels to the best of their ability (Armitage, 1958). Only after reviewing the literature and understanding the pest better, did the decision makers appreciate the situation. They learnt that the pest does not infest fields and does not fly. Therefore, each infested premise could be progressively eliminated through eradication and further spread could be prevented through enforcement of strict controls (Armitage, 1958). Success seemed limited only by the ability to detect all infestations. To assist with delineating the pest Howe and Lindgren (1957) estimated the likely area suitable for the khapra beetle based on preferred development temperatures and humidity. However, because environments within storage buildings are independent to ambient conditions they suggested surveys continue in heated premises and any self-heating commodities that were outside of the suitable areas.

At least 151 sites in 23 counties were detected in surveys by early 1955 (Lindgren et al., 1955). Initial surveys had revealed 121 infested premises in 16 Californian counties; 27 in five Arizona counties; and 3 in two New Mexico counties. Three infestations were also found in parts of Mexico, such as Baja California Norte. Armitage (1958) reported that 51,000 premises in 27 states had been inspected and 419 infested premises were identified, of which 272 were in California, 107 in Arizona, 5 in New Mexico, and 35 in Mexico. The total premise volume to be eradicated was 3.2 million cubic metres (Armitage, 1958). By 1959, around 580 infestations were identified (Lindgren and Vincent, 1959; Myers and Hagstrum, 2012). Mills and cereal processing facilities were found to be the foci of most of the infestations. In Arizona, surveys showed that infestations were found in major agricultural and cattle-feeding cities and towns (Nutting, 1984). The California Department of Agriculture was first to decide to attempt eradication of all infestations within its borders, primarily because it had the largest farm value of the three infested states (Armitage, 1958). However, Arizona and New Mexico quickly followed in the decision to eradicate also (Armitage, 1958). In a first, Arizona attempted to regulate a storage pest with intrastate quarantine, but it was postponed for about a year after detection due to legal issues raised (Mendenhall, 1956; Nutting, 1984). This triggered eighteen other state quarantines to be implemented against Arizona and California, which caught the attention of the country and the Federal Government (Mendenhall, 1956). The United States Department of Agriculture (USDA) recognised the value and effort of the program and took over responsibility to generate uniformity across all states and gain co-operation from the authorities in Mexico (Armitage, 1958). Local, state and federal authorities were assigned with the implementation of the control treatments and eradication programs (Lindgren and Vincent, 1959).

Armitage (1958, 1956) and Mendenhall (1956) describe the eradication program in detail and is summarised here. Having had limited experience with such a situation it was not known how to action the actual eradication process. Thus research agencies and commercial firms were engaged to establish appropriate control measures. The most promising option was gas tight covers over buildings and fumigation. However, the need to cover the whole structure or multiple structures with a non-leaking cover equivalent to a single cover was a challenge. The chosen fumigant was methyl bromide, because of its proven effectiveness at all life stages, and its non-explosive, non-inflammable and less toxic characteristics, even though it was known to disperse poorly in large grain masses. Prior to launching the program three trials were run with success at large premises sized between 15,300 and 28,300 cubic metres, with and without barley storage. In time the process evolved to become more effective. In severe infestations, insects had been found up to 15 metres from the building. Therefore to avoid reinfestation from external insects the area up to 30 metres outside of the infested building was sprayed, raked in towards the building and fumigated under the cover. Air trapped within the cover required extraction to prevent tears and avoid heat expansion and ballooning. The program faced many problems, the most significant were the wind and weather; reaching and maintaining the gas concentration level; and release of the residual gas at completion of the fumigation. When the gas was released from the building at low temperatures or high humidity the gas would hang close to the ground and spread at concentrations well above tolerable levels. Therefore, the gas needed to be released during the heat of the day, or the fumigant forced upwards with fans. Sourcing and managing the necessary equipment and the large building covers was no easy feat either. For example, the area of one plasticised nylon cover used was approximately 40,000 m^2 in size. At another location the cover needed to encase approximately 113,000 cubic metres, and required approximately 14,000 m^2 of material. In 1958, some covers were reported to cost USD $47,500 - $60,000. Clamps were used to hold the fumigation tarpaulins together and at one site over 35,000 clamps were needed.

Infested properties with the highest risk of outward spread were given priority for fumigation, particularly those that held and moved host materials. Of least priority were infested premises that had on-farm host material stored for on-farm use. Owners and businesses of infested properties found themselves black-listed while under the quarantine status, and businesses were greatly impacted by disruption, avoidance and expenses. The actual losses caused by the pest were not that significant, but in heavy infestations weight losses up to 20% in sorghum and 30% in barley could be expected after two years (Nutting, 1984). The real impact came from control measures, treatments and quarantine regulations that affected trade within and between states (Mendenhall, 1956). In Arizona, quarantine was placed on entire counties with infested properties (Nutting, 1984). Movement of any stored commodities out of the regulated counties required permits regardless of whether the property was infested or not (Nutting, 1984). If commodities were coming from an infested property they had to be treated prior to movement. However, the quarantine restrictions imposed by other states on Arizona, California and New Mexico prohibited an extensive host range of commodities from being imported under any condition (Nutting, 1984). In Arizona, the million-dollar trade of certified sorghum and barley seed bore large losses due to infestations in processing facilities, costly fumigation treatments and poor germination post-fumigation (Mendenhall, 1956). Businesses that had infested establishments were also rejected as government storage sites, and the Grain Exchange refused to give prices for grain from these premises. Costs to industry during these months were not calculated but considered to be significant. To relieve businesses from the quarantine burden sooner, an agreement was made that the infested quarantine status be removed immediately after the premises had an all-over fumigation under gas-tight covering and evidence was given that the recommended dosage and duration was achieved. If another type of fumigation was applied under official supervision, exemptions were given subject to inspections, but approval was delayed for a minimum of one year. When Armitage published his report of the outbreak in 1958 no fumigated premise had been reinfested.

Mexico had 92 properties infested and successfully eradicated by 1961 (Myers and Hagstrum, 2012). By mid-1962 all infestations in the U.S. and Mexico were thought to be found, and by the end of 1963 they had been treated and released from quarantine measures (Nutting, 1984). During 1963, inspections of almost 32,000 properties in 37 states had not revealed a single khapra beetle. In 1964, eight new infestations were detected in Arizona at places like a chicken ranch, feedlot, feed mill and in grain stored at an agricultural college campus (Nutting, 1984). They were all fumigated and understood to have been from one source. Another 14,000 inspections took place in 28 states in 1965. By 1966 the pest was considered completely eradicated, and the U.S. and Mexico program had cost between USD $11 - $15 million (Barak, 1989; Myers and Hagstrum, 2012), equivalent to approximately USD $96 – 130 million in 2016 dollars. Early in the program Armitage (1958) stated that California bore the entire cost until the Federal Government took over and covered one-third by suppling materials and personnel; Arizona split the cost three ways between the State, Federal Government and the property owner; in New Mexico infested property owners covered costs with some Federal aid; in Mexico the U.S. made significant contributions in money and personnel. The spending share was 56% by Federal Government and 44% by property owners (Klassen 1989 in Myers and Hagstrum 2012). Nutting (1984) reported in the 30th anniversary paper that the occasional small infestation was still being detected and eliminated. He also commended the few insect taxonomists that had to identify conclusively whether the thousands of specimens collected were khapra beetle. Their classification was to decide if expensive fumigation was to occur or not. The costly eradication program was deemed the only rational way to control the khapra beetle (Nutting, 1984).

More eradications took place after infestations were detected between 1978 and 1997 in food processing facilities, a spice processing warehouse, and other protected facilities in California, Maryland, Michigan, New Jersey, New York, Pennsylvania and Texas (French and Venette, 2005). In the case of the spice processing warehouse, fumigation of the facility was met with citizen objection and only fumigation of departing shipments and surface spraying with malathion could take place. As a one off, the equipment was also replaced coinciding with the planned facility upgrade (Pasek 1998 in French and Venette 2005). The 1978 infestations were eradicated by 1983, and the smaller infestation in 1997 was much quicker (Stibick, 2007). Since these large post-border outbreaks eradication programs have generally been at a domestic level. For example, at a house in Connecticut in 2006 after an isolated infestation was detected (Myers and Hagstrum, 2012; Stibick, 2007). In early 2013 live khapra beetle larvae were found by Customs and Border Protection (CBP) at Pembina, North Dakota in a seemingly low-risk shipment of clothes moving from Alberta to Texas (USDA-APHIS, 2013a).

The following summarises some of the more recent intercepts of various life stages and forms of khapra beetle at Preclearance Facilities, airports and ports by the U.S. CBP in passenger luggage and imported goods (U.S. Government, 2016). In 2014, larvae and cast skins were detected in dried pigeon peas in passenger luggage arriving from Sudan; in a traveller's rice package from Saudi Arabia; and stopped in Abu Dhabi, United Arab Emirates in dried chick peas destined for the U.S. In five cases in Dallas, passengers had not declared packages of rice, dried beans, coriander seeds and fava beans from Sudan and India that carried cast skins and live larvae. At the Lewiston Bridge on the Canada and U.S. border, three live larvae were detected in a sea container being hauled into the U.S carrying a shipment of rain ponchos from China. Three interceptions of khapra beetle were reported at the Port of Norfolk, Virginia in 2014-2015. The first two intercepts were in organic soybeans from India in November 2014, and the third in split lentils and spices from United Arab Emirates in January 2015. Other live intercepts in 2015 include, declared rice from Saudi Arabia via London; a 2 kg bag of dried beans originating from Somalia; undeclared dried chick peas and peanuts originating from India; and a 13.7 tonne shipment of chickpeas, lentils and other Indian foodstuffs refused entry and re-exported. Cast skins were also detected on dried hibiscus leaves that were packaged with other plastic bags of rice and spices from Iraq. In early 2016, a 25 tonne shipment of cumin seed from India infested with dead larvae was sealed and re-exported. Even when khapra beetle is found in a dead state the U.S. CBP takes regulatory action against the pest (U.S. Government, 2016).

A pest risk assessment for khapra beetle in the U.S. was conducted in 1998 by Pasek and reviewed more recently by French and Venette (2005). Notably there was a shift in the economic impact from moderate to high. Reasons given for the change was the potential that establishment of the pest could reduce the volume and quality of affected products and result in international trade implications. The total value of exports of susceptible grains, rice, nuts, flours and mixes in 1993 – 1997 to countries other than the Middle East and North Africa was approximately 18% of the value of the principal U.S. agricultural exports, representing a total of USD $11 billion per year (Pasek 1998 in French and Venette 2005). Conversely, it was noted that the availability of control treatments may mitigate the risk impact downward to moderate. The U.S. risk evaluation summary is below in Table 3.

Table 3. Summarised risk assessment of khapra beetle to the United States. Source: French and Venette, 2005

High	Moderate	Low
Likelihood and consequences of khapra beetle establishment	Entry potential	Host availability
Potential economic impact (previously moderate)	Environmental impacts (previously high)	Taxonomic recognition
Ecological suitability		
Host specificity		
Survey methodology		
Destination of infested material		

Improved border detections in the U.S. have contributed to an enormous increase in the number of khapra beetle interceptions over the years. From 1985 to 2010 khapra beetle was identified 559 times of the total 666 *Trogoderma* species intercepted (Myers and Hagstrum, 2012). About a half of the detections were found in passenger luggage, approximately 30% were in general cargo and the remainder in mail, ship holds and stores, and other cargo (Myers and Hagstrum, 2012). During 1985 and 1998, 63% of introductions were via airports and 36% at ports (Stibick, 2007). Authorities were prompted to introduce additional import restrictions when over 300 interceptions were reported in 2011 and 2013, and a spike of more than 550 were reported in 2012 (Myers et al., 2013; USDA-APHIS, 2012a). More than 43 countries were identified as the originating country, but the majority of intercepts were from India, Saudi Arabia, Pakistan and Iran. Asia and the Middle East and North African regions accounted for 88% of the originating countries of interceptions at U.S. ports during 1984 – 2010, (Figure 3) (Myers and Hagstrum, 2012). In 2012 the restrictions or prohibitions were increased on the commercial or non-commercial importation of rice, soybeans, "Cicer" species such as chickpeas, and safflower seeds from countries known to have khapra beetle (USDA-APHIS, 2012a). For the 2014 fiscal year (October 2013 to September 2014) 197 khapra beetles interceptions occurred, and by April 2015 there had been 98 (U.S. Government, 2016).

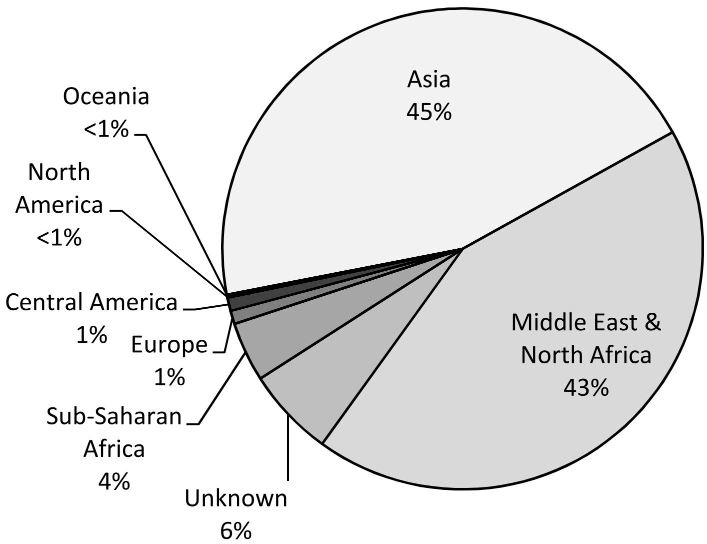

Figure 3. Region of origin of the interception of khapra beetle at U.S. ports from 1984 to 2010. Australia was the only country included in Oceania. Source: Myers and Hagstrum, 2012

To assist U.S. port inspection procedures the United States Department of Agriculture – Animal and Plant Health Inspection Service (USDA-APHIS) established preclearance programs with some exporting countries (Myers & Hagstrum 2012). Preclearance aims to benefit both countries by having inspection, treatment and other measures take place in the exporting country prior to arriving at the U.S. This shifts the cost and responsibility to the exporting country in return for a quicker transition to market upon arrival in the U.S. (Myers et al., 2013). The Preclearance Facilities also inspect passenger luggage prior to entering the U.S. and in 2015 the Toronto and Port of Dublin facilities had their first intercepts of khapra beetle.

During 2012 – 2014 a national khapra beetle survey project with planned spending of approximately USD $535,000 across the states was being run, and approximately USD $130,000 to be spent on development for new treatment options for khapra beetle (USDA-APHIS, 2014, 2013b, 2012b).

Khapra beetle is not considered established in the U.S. and therefore remains as a non-khapra beetle country. Any future detection of khapra beetle is likely to be met with rapid control and eradication.

5. Khapra beetle: In other countries

Lindgren, Vincent and Krohne (1955) give a literature review of khapra beetle detections and information established about the pest in the years between 1916 and 1954. The paper describes imports from India as the primary source for the pest entering into other countries and about the detections in England, Germany, Korea, Japan, U.S.S.R., Sudan, Nigeria and California in the U.S. Various fumigation, spray and dust treatment procedures were used and tested, including chlorine gas, chloropicrin, carbon disulphide, cyanide-based Zyklon, tetrachlorethane, calcium cyanide and pyrethrum during this period to control khapra beetle in stored product warehouses.

The established distribution of the pest at this time was described as India, Ceylon, Malaya, Europe, U.S.S.R., China, Japan, Korea, Philippine Islands, Madagascar, Cyprus, Nigeria, Mexico, parts of the U.S., England, Germany and Australia (Armitage, 1958; Hinton, 1945; Lindgren et al., 1955). During 1957 and 1973, 46 to 131 interceptions of khapra beetle were detected each year in imported commodities entering England (Freeman 1974 in Myers and Hagstrum 2012). The insects were found mainly in rice and peanuts from Burma, India, Nigeria and Sudan.

5.1. Japan and Korea

Khapra beetle was first reported in Japan in 1923 and was absent by 1950 when the law to inspect imported stored products was introduced (Sonda, 1968). Korea had also reported khapra beetle in 1928. But there is uncertainty about the correct identification of both of these reports (Sonda, 1968). A nation-wide search for khapra beetle began in Japan after complaints of a Dermestid beetle in breweries in 1964 (Sonda, 1968). Almost 30 properties were inspected, and the focus was on breweries and maltings. The insect was found at four breweries that were some distance from each other and in two maltings that supplied these breweries. The infested breweries belonged to one company and the likely source of the incursion was brewing supplements such as broken rice and hessian bags from Southeast Asia. An eradication program involving fumigation with methyl bromide at infested premises, and filling crevices of warehouses and silos with mortar was undertaken (Sonda, 1968).

5.2. Africa

Viljoen (1990) reported on the history and experience of South Africa, Zimbabwe and Zambia with khapra beetle and describes the occurrence and disappearance of populations. The first record of khapra beetle in South Africa was in a premise in Pietermaritzburg. The pest was in malt imported from England in May 1953, but no further insects were found after the malt was processed into beer. In June 1955, a heavy infestation was detected in a stack of sweepings and tailings in a mill at Bon Accord near Pretoria. The introduction could have been from a number of sources over three years, but no spread had occurred beyond the stack. After milling as stock feed the area was sprayed with insecticide and no more insects were found. Between 1972 and 1974 a large scale detection and eradication program ran after the discovery of a severe infestation in the small and remote wheat production area of Onseepkans in February 1972. This region had not been carrying out regular pest control and believed their risk for pests was low due to the dry climate and the grain's short time in storage. After discovery of the infestation, consignments were fumigated prior to dispatch to the Upington mill. However by June, 10% of kernel samples were severely damaged. The khapra beetle infestation was found to be widespread throughout the storage buildings and empty farm stores of the settlement, and also at two stock farms in Namibia. A widespread fumigation and surveillance program took place with all infested storage buildings fumigated under tarpaulins with methyl bromide and sprayed with malathion. In an effort to identify the source all seaport warehouses and grain elevators were examined during 1973 – 74, as well as major spice importing merchants' store-rooms, but no *Trogoderma* were detected. The source was never determined, but anecdotally the pest had been present in the region for years. Khapra beetle had previously been recorded as present in Zimbabwe, Zambia and Malawi in the 1950s. In Zimbabwe, infestations were found in imported beans, a stack of sievings, a storage shed next to a silo and later the silo itself, and also in grain delivered to the Grain Marketing Board of Zimbabwe. Fumigation practises were then improved, moving from BHC, DDT and layer dusting with lindane to routine methyl bromide fumigation and frequent spraying of malathion. Detections in Malawi never resulted in large-scale outbreaks, perhaps due to routine fumigation in central storage facilities. No outbreaks have been reported in Botswana or Mozambique, although the infested beans imported into Zimbabwe in 1955 were from Botswana. In 1990 at the time of Viljoen's paper, khapra beetle was not known to occur in Zimbabwe, Zambia, Malawi or South Africa with populations either eradicated, died out or too low to detect. In addition to improved pest control, factors likely to contribute to the temporary establishment of the pest are the unsuitable climate, poor competition with other storage pests and small grain stores for short periods of time.

5.3. New Zealand

Khapra beetle is not present in NZ. However, introductions have been intercepted as early as March 1964 when adults and larvae were found in cargo arriving in Dunedin, New Zealand (NZ) from South Africa (Ward, 1965). More recently the Ministry of Agriculture and Forestry of NZ assessed the biosecurity risk of importing new and used vehicles and machinery, including the risk of introducing khapra beetle. Assessment found 2 – 4 % of vehicles entering NZ were contaminated with Dermestid beetles, this is expected to be an underestimate because specimens are not always identified to the species level (Biosecurity New Zealand, 2007). Between 1994 and early 2006 only one intercept was recorded for live khapra beetle larvae and pupae in used vehicles from Japan. Any vehicles with evidence of Dermestid beetles are fumigated. However, if the vehicles are vacuumed prior to inspection less fumigations are needed although the efficacy of vacuuming is unknown. At the port of Auckland, 3.1% (2,147) of used vehicles required fumigation in the 19 months from January 2004. In 2006, sixty specimens taken from used imported vehicles from Japan revealed that 95% were *Anthrenus verbasci*, the already established varied carpet beetle. The report makes the statement that "*… trade between Australia and countries such as India where the beetle is commonplace has been carried out without rigorous quarantine measures for many years*" and suggests that climate may be why it has not become established in Australia and NZ (Biosecurity New Zealand, 2007). However, the ease at which khapra beetles can enter vehicles and machinery, the difficulty of detection and identification as well as the potential country-wide movement, sets this import pathway at a high risk. But the risk of establishment via this pathway is considered negligible, with the exception of agricultural machinery and trucks that are likely to be taken to a suitable environment for establishment. Economic and human health consequences as a result of entry and establishment of khapra beetle are rated as high for New Zealand.

5.4. Vietnam

The Asia and Pacific Plant Protection Commission (APPPC) report that khapra beetle was intercepted on imports of coconut oil-cake from Indonesia, and in wheat bran from Sri Lanka entering Vietnam in 2007 – 2009 (APPPC and FAO, 2011). In 2010, khapra beetle was intercepted on corn, soya bean, barley and millet imported from India. A further 104 consignments from India detected khapra beetle by early 2011.

6. Methyl bromide and options in the future

Options to deal with khapra beetle infestations are limited. Methyl bromide is the most effective fumigant in the treatment and control of khapra beetle. However, methyl bromide usage restrictions enforced in recent years are set to increase in the future leaving very few other effective options. The Montreal Protocol has been the driving mechanism to phase-out the use of major ozone depleting chemicals and other environmentally damaging products, including methyl bromide which was listed in 1998 (Porter et al., 2009). Approximately 8,000 -

10,000 tonnes was used per year globally for the purpose of Quarantine and Pre-shipment (QPS) in the 1990s, and 10,250 tonnes in 2007 (Porter et al., 2009). As well as specific QPS exemptions, critical use exemptions are approved when there is no technical or economical alternative available. Since 2003, methyl bromide used under critical use exemptions had declined from 17,000 tonnes to less than 5,000 tonnes in 2007 (Porter et al., 2009). The importance and effectiveness of methyl bromide in biosecurity has led to the development of recapture and recycle systems and technology as a means to extend use and avoid letting the product escape into the atmosphere (DA, 2015b; Porter et al., 2009). Recapture units are currently available and in use. However, the use of methyl bromide is still restricted by the Montreal Protocol and further phase-out restrictions for biosecurity purposes are expected (Porter et al., 2009). Also, as the overall reduction in demand for methyl bromide takes effect the cost of production is expected to increase substantially and product supply may become scarce (DA, 2015b).

USDA-APHIS is currently evaluating the efficacy of other registered insecticides as alternatives. Over USD $500 million has been spent in the U.S. investigating alternatives to methyl bromide for soil disinfestation alone (Porter et al., 2009). To overcome the difficulty in testing against khapra beetle outside of an approved quarantine facility, the warehouse beetle is being tested to determine if it is a suitable surrogate species (Myers et al., 2013). The primary fumigants listed by USDA-APHIS in response to khapra beetle are methyl bromide where possible, and phosphine as the alternative (Stibick, 2007). If there are signs of methyl bromide resistance or the site is too close to human populations, phosphine is recommended. A phosphine treatment can be more costly due to the extended period required for effective fumigation. Suggested replacements by USDA-APHIS for methyl bromide and phosphine, although not necessarily fully tested or approved are sulfuryl fluoride, ethylene oxide, ethyl formate, hydrogen cyanide, nitrogen gas, heat, heat with carbon dioxide, biogas and irradiation (Stibick, 2007). Alternative plant derived options are lemongrass oil and Neem EC. Other alternatives under investigation are the protozoa *Mattesia trogodermae* and a vitamin B-complex Biotin. The *Laelius pedatus*, a parasitoid of the khapra beetle has also shown potential as a biological control agent under the right conditions. Eliopoulos (2013) summarises possible options and limitations for the future management of khapra beetle from past and present studies, including novel and traditional strategies. Despite the volume of literature no particular strategy is presented as an optimal solution. Critical outstanding issues noted by Eliopoulous (2013) and Cunningham (2012) were the need for rapid, simple, reliable identification and improvements in detection, phytosanitary measures, traps and attractants. They suggested more important matters that require attention as the need for new fumigants and contact insecticides, a concerted effort to avoid resistance development, and control the usage of chemicals that have the potential of becoming a long term solution to prevent resistance developing (Eliopoulos, 2013). Perhaps an even more challenging task is gaining approval of new treatments as a sufficiently suitable quarantine strategy.

7. Economic implications

Evidence from the incursion in WA has shown that Australia has the necessary experts, know-how and methods for a successful eradication in a small contained environment post-border. The climatic conditions at Australian coastal ports and urban centres are not overly favourable for the pest with the exception of Adelaide SA (Botha et al., 2005). However, many inland grain growing regions and grain storage facilities are located among the more climatically favourable regions. Unless there is unprecedented spread and establishment to all of the Australian grain supply and distribution sites without prior detection or control, khapra beetle infestations can be limited. Assuming khapra beetle will not necessarily be widespread initially, particularly throughout all grain storage and distribution centres in Australia at the same time infestations will likely be in isolated facilities or regions similar to the many infestations detected in the U.S. Established infestations can be expected to add additional costs for fumigation, grain cleaning, quality downgrades, and in a worst case scenario the grain is unused and wasted. Further implications can be expected from international trade sanctions that may be imposed, or potentially absolute loss of certain markets. McElwee (2000a) described that establishment would lead to direct losses to stored grain; an increase in treatment control costs for export; and the potential to have export restrictions imposed, such as grain to be sourced from regions free of the pest; or total abandonment of grain exports from the infested region or Australia as a whole.

The presence of the warehouse beetle in Australia has had minimal impact on trade, but has complicated detection of khapra beetle in adult and larva form due to their superficial resemblance. A 2008 survey of WA grains industry members found respondents were least likely to detect, or recognise khapra beetle or the signs and symptoms than other high priority pests such as barley stripe rust (*Puccinia striiformis* f.sp. *hordei* Eriksson 1894) and Karnal bunt (*Tilletia indica* Mitra 1931) (Hammond et al., 2016). As a consequence of allowing warehouse beetle to establish, there is now an additional serious risk that the khapra beetle may establish and go undetected, delaying any response that would have otherwise been taken. Similarly, the risk of misidentification, like in the 1940 - 50s, could occur if the warehouse beetle is found in Australian exports. Detection of a *Trogoderma* species in a shipment of exported grain risks financial losses in deferment while the insect is being identified, disinfestation costs, and potential rejection and relocation of the shipment (Viljoen, 1990). A costly campaign to prove freedom from khapra beetle may arise once again.

For a more detailed assessment of targeted surveillance programs for khapra beetle McElwee (2000a) suggested the following is required*:*

(a) estimation of the potential impact of an uncontained outbreak of khapra beetle in Western Australia;
(b) quantification of the effect of early detection on emergency response costs, trade restrictions and the probability of emergency response success;
(c) evaluation of the relationship between level of surveillance expenditure and the effectiveness of surveillance; and
(d) assessment of the trade-off between spending on targeted surveillance versus improved barrier quarantine."

In recent years WA has often had the largest production volume of wheat and coarse grains in Australia. In good years WA has contributed between 30 and 47% to the nations' wheat production and 27 - 34% of coarse grains since 2006-07 (ABARES, 2013). Had the eradication not been successful, trading countries could have imposed a ban on Western Australian wheat and other host grain exports. Reasons given could have been that the receiving country was a non-khapra beetle country or countries already infested were concerned about importing a more tolerant or resistant khapra beetle. In 2012-13 WA wheat export value was AUD $2.7 billion, and approximately AUD $1.8 billion in each of the two years prior (DFAT, 2014). Significant cost has been saved as a result of the successful eradication of khapra beetle and continuation of trade. Susceptible products exported from Australia to countries listed as khapra beetle and non-khapra beetle countries from 2006 to 2013 is shown in Figure 4 in terms of value. Although the value of exports to khapra beetle countries has increased over the years, the potential market losses of trade with non-khapra beetle countries in 2012 and 2013 is approximately AUD $5.5 billion per annum.

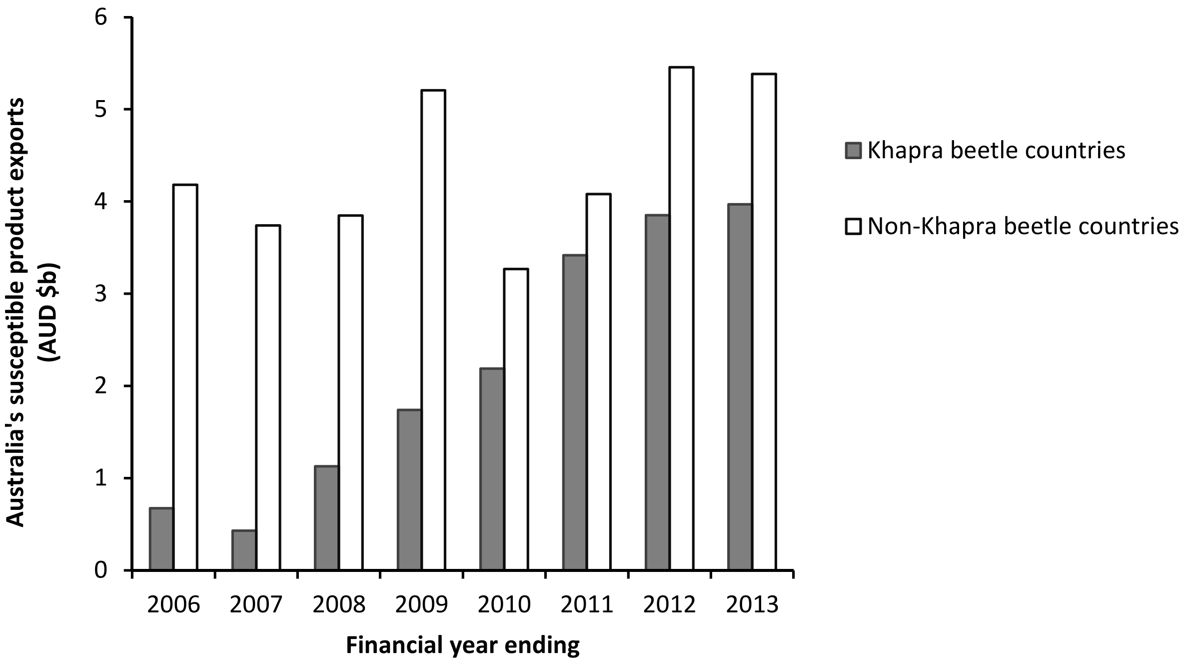

Figure 4. The value of Australia's susceptible product exports to khapra beetle and non-khapra beetle countries. Products include wheat, rice, barley, maize, other cereals, wheat flour, other cereal flours and cereal preparations. Countries selected as khapra beetle countries are those listed by the Australian Government Department of Agriculture. Source: DAWR, 2016b; DFAT, 2014

8. Discussion

This paper takes the 2007 WA khapra beetle incursion as a starting point to understand decision making in relation to a biosecurity response. The WA khapra beetle post-border incursion was successfully eradicated in a relatively short time period and therefore the lessons learnt are somewhat limited. Although, the cost of around AUD $200,000 for the eradication of the pest from a single house is negligible with respect to the value of the grains industry, it is indicative of the high cost that can be expected of an eradication campaign for a more extensive outbreak. As the number of properties infested rises the requirement for fumigation and surveillance extends and increases rapidly, as do the costs.

The paper then considers the warehouse beetle outbreaks in Australia during 1977 and 1993. Despite a cost benefit ratio for eradication in WA of around ten to one, it was decided to move to a containment strategy. This strategy was pertinent when the cost to eradicate the pest from a larger number of houses and building structures exceeded available resources for biosecurity. Furthermore, success in the eastern states was unattainable. It was also implied from this review that the social costs of eradicating across towns would be prohibitively expensive. When considering five key factors (i) ability to spread; (ii) rate of spread; (iii) potential damage and economic impact; (iv) cost to eradicate; and (v) likelihood of eradication success, containment of warehouse beetle was likely to be an optimal strategy. Given the nature of warehouse beetle, it can be characterised as a pest that can fly; disperse quickly and widely itself and by humans; damages a range of stored and processed products, but not to devastating levels; and expensive and difficult to eradicate once it is widely distributed. The warehouse beetle is not a trade sensitive pest and damage costs are less than that of khapra beetle. Thus, containment was selected as the ongoing strategy. Early attempts of eradication were futile due to a failure to delimit the extent of the pest across WA. Surveillance and delineation initially may have led to an early detection of the warehouse beetle, albeit at a wider, but potentially eradicable distribution. In future, containment is likely to be an optimal strategy unless the pest is detected early and accurately delineated.

Conversely, when might it be optimal to cease eradicating a khapra beetle outbreak? There is abundant evidence from the U.S. and around the world that repeated and large scale eradications would be warranted. Continued eradication efforts would be justified because the khapra beetle cannot fly and has poor dispersal ability; spread is primarily aided by humans; the damaging effects on stored grain is severe; and loss of export markets is certain. Surveillance and delineation of khapra beetle will be made more difficult with the presence of the warehouse beetle across Australia and will undoubtedly complicate the identification process and put a strain on resources. The cost of a widely dispersed khapra beetle incursion is likely to run into the billions of dollars. However, there is no reason that the incursion should spread quickly, and once identified infested storage structures would be quarantined and subjected to intensive fumigation. This process could be repeated until eradication was achieved locally, regionally and finally nationally. The biology of this pest determines the optimal economic decisions. Khapra beetle damage potential has a high cost. However, it is an immobile slow dispersing pest that depends upon discrete storage structures. It can be detected through trapping and there is an eradication treatment, methyl bromide. This treatment is relatively high cost compared to phosphine, but the cost is justified by its effectiveness and safeguarding the continued use of a storage facility. A containment strategy may only be considered in the future if there is no fumigant available. For instance, if methyl bromide is completely banned, or a widespread outbreak occurs across a residential area and the social cost of fumigating houses is excessive. In this case a containment strategy for urban areas may need to be combined with protection of storage facilities by strict surveillance and periodic eradication episodes.

Border security programs alone are not sufficient to intercept all introductions of khapra beetle with the movement of people and goods globally. Khapra beetle incursions will be an ongoing problem and whilst well-trained staff and the vigilance of trading and transport companies are a strategy to protect countries, many of the detections are reported by the public post-border. This raises concerns about whether current levels of awareness about khapra beetle in the metropolitan and rural community are enough, in particular the importance of informing the regulator immediately. Timing of detection and response can be the difference between a small local fumigation and a wide-spread eradication program. Several more points of concern are raised with regards to future response strategies. Firstly, the state of preparedness for a future with increased interceptions, incursions and eradications, increased khapra beetle resistance to commonly used fumigants and the absence of methyl bromide. Secondly, without improved detection methods and a decline in resources to rapidly identify khapra beetle the risk of spread and reliance on low-cost surveillance by individuals in the community to report sightings increases. Finally, is there a khapra beetle outbreak threshold? Is there a size, scale and duration that a khapra beetle outbreak can extend to before the country is declared as endemic and a khapra beetle country? It seems if deemed to be under management, even with repeated outbreaks a country can continue to trade, although perhaps with increased phytosanitary measures and costs applied.

9. Conclusion

History has shown us that post border detection of khapra beetle has been slow in the United States, Japan, Korea and South Africa. This has led to the spread of the pest to a wider distribution than would have occurred had it been correctly identified initially. The khapra beetle has been mistakenly identified and disregarded on numerous occasions with other similar pests such as the black carpet beetle or warehouse beetle. Post-border detection has depended on formal and informal reports of the pest to authorities primarily once the infestation population has reached detectable levels, there is a noticeable distribution of the pest or an obvious amount of damage has occurred. In the past, the response has been slow for reasons such as misidentification, going undetected, or simply no prior preparation or information about the biological characteristics of the pest and effective eradication methods. The United States were the frontiers in khapra beetle eradication, undertaking a large scale eradication program consisting of the fumigation of over 600 sites of infestation and undertaking approximately 97,000 property inspections at a cost of USD $96 – 130 million in 2016 dollar value. Once the decision makers knew the pest did not infest fields and does not fly, they decided that success was only limited by the ability to detect all infestations and elimination could occur progressively. Although issues with the legalities of regulation of intrastate quarantine were raised, they were resolved over time and strict statutory movement controls were considered sufficient to stop the spread. Eradication was possible with progressive elimination of the pest, and fumigation locations with the highest risk of outward spread were given priority. The actual losses from damage are not that significant, but the real impact comes from control measures, treatments and quarantine regulations that affect trade. It was beneficial for the United States to support Mexico financially and with resources to limit the potential risk of reinfestation. It was also beneficial that such programs had community support to allow the eradication process to take place.

The positive component of the warehouse beetle eradication attempts across Australia was in knowing when to surrender. The success of the khapra beetle eradication program in Western Australia came from preparedness, the small scale infestation and limited distribution, agreement and cooperation across government, industry and community, and the technical feasibility of the fumigation. A larger scale infestation can be expected to be more costly and difficult, but worthwhile to avoid additional fumigation expenses, price penalties or trade embargoes. Improved detection methods in the United States have resulted in more khapra beetle intercepts at its borders. This should be used as a warning to Australia about the risk of future post-border entry and our preparedness for the next khapra beetle incursion.

This paper is a prelude to our current research directed towards optimising the response strategy for khapra beetle incursions. The bio-economic model developed simulates spread and detection and identifies optimal response strategies such as eradication, surveillance distances and surveillance effort or intensity. Early results indicate that rapid eradication response is the most cost effective response and success is achieved within two years almost always for smaller metropolitan incursions.

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12. Appendix

12.1. Acronyms and abbreviations

AFAS	Australian Fumigation Accreditation Scheme
APPPC	Asia and Pacific Plant Protection Commission
AQIS	Australian Quarantine and Inspection Service
CBH	Co-operative Bulk Handling Group
CBP	Customs and Border Protection (U.S.)
CCEPP	Consultative Committee on Emergency Plant Pests
CRCNPB	Australian Cooperative Research Centre for National Plant Biosecurity
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFWA	Department of Agriculture and Food Western Australia
EPP	Emergency Plant Pest
EPPRD	Emergency Plant Pest Response Deed
FAO	Food and Agriculture Organization of the United Nations
MGC	Metro Grain Centre
NMG	National Management Group
PBCRC	Plant Biosecurity Cooperative Research Centre
PIRSA	Department of Primary Industries and Regions South Australia
PLANTPLAN	Australian Emergency Plant Pest Response Plan
SAP	Scientific Advisory Panel
SPCHQ	State Pest Control Head Quarters (DAFWA)
USDA	United States Department of Agriculture
USDA-APHIS	United States Department of Agriculture – Animal and Plant Health Inspection Service

12.2. Timelines

a) Overview of Australia's preparedness and response to khapra beetle incursions

1998 – 2005	**Preparedness**	Pre-emptive and preventative assessment and threat contingency plan prepared.
15 March 2007	***Undetected post-border incursion WA***	
18 - 20 April 2007	**Investigation phase**	Incursion suspected in WA and pest identified.
23 April - 3 May 2007	**Alert phase**	Pest confirmed, response plan prepared and approved.
Early May 2007	**Operational phase**	Eradication program initiated, house fumigated and other locations sprayed.
June 2007 – June 2009	**Two year trapping program**	in WA and Qld houses, depots, shipping and recycling facilities.
August 2009	**Stand down phase and eradication a success**	No further action and review.
≤ May 2016	***Undetected post-border incursion SA***	
20 - 24 May 2016	**Alert and Operational phase**	Detected in 3 premises in SA. Eradication, surveillance and tracing initiated.
2016	**Currently khapra beetle free**	

b) Preparedness (Pre-emptive and preventative assessment, and threat contingency plan prepared)

1998	**Agreement to review Quarantine status of khapra beetle**	
1999	**A review of biology, distribution, monitoring and control**	prepared by Rees & Banks, CSIRO.
< 2005	**Threat Data Sheet**	prepared by DAFWA, included Emergency Response Plan.
2005	**Threat-Specific Contingency Plan**	prepared by DAFWA
15 March 2007	***Undetected post-border incursion WA***	
2007	**Incursion**	Emergency Response Plan prepared within 10 days of incursion detected.
2007	**Emergency Response Plan approved and implemented**	within 13 days of incursion detected.
≤ May 2016	***Undetected post-border incursion SA***	
2016	**Emergency Response Plan approved and implemented**	within days of incursion detected.
2016	**Currently khapra beetle free**	

c) Phase 1 - Investigation (Incursion suspected WA) 36 days

15 March 2007	***Undetected post-border incursion WA***	
15 March 2007	**Sea container arrived**	in Fremantle from Scotland via a number of ports.
23 March 2007	**Inspected by AQIS**	Content re-packed into another container and stored at depot.
3 April 2007	**Delivered to house by road**	Personal effects arrive, but not unpacked.
18 April 2007	**Unpack and discover**	live beetles, larvae and castes in a host of non-food personal and household items.
19 April 2007	**Report to pest controller**	Suspected introduced species. Report to AQIS/DAFWA.
19 April 2007	**Site identification and specimens collected**	from infested house. Five neighbouring houses at risk.

d) Phase 2 - Alert phase (Pest confirmation, extent, consequences, response assessment WA) 14 days

15 March 2007	***Undetected post-border incursion WA***	
20 April 2007	**Khapra beetle identified**	by DAFWA Senior Entomologist by 12 pm.
20 April 2007	**Residents moved out**	voluntarily with minimal belongings by 7 pm.
21 April 2007	**Garage fumigated**	Preliminary and precautionary measure.
23 April 2007	**CCEPP agreement**	EPP Category 2 pest detected. EPPRD and PLANTPLAN to be followed.
26 April 2007	**Khapra beetle confirmed**	by CSIRO Entomology, Canberra.
30 April 2007	**CCEPP endorsed draft Response Plan**	Scientific Advisory Panel formed to consider trapping and monitoring program.
3 May 2007	**NMG (and CCEPP) approved**	Response Plan for implementation and national cost-sharing of $169,500.

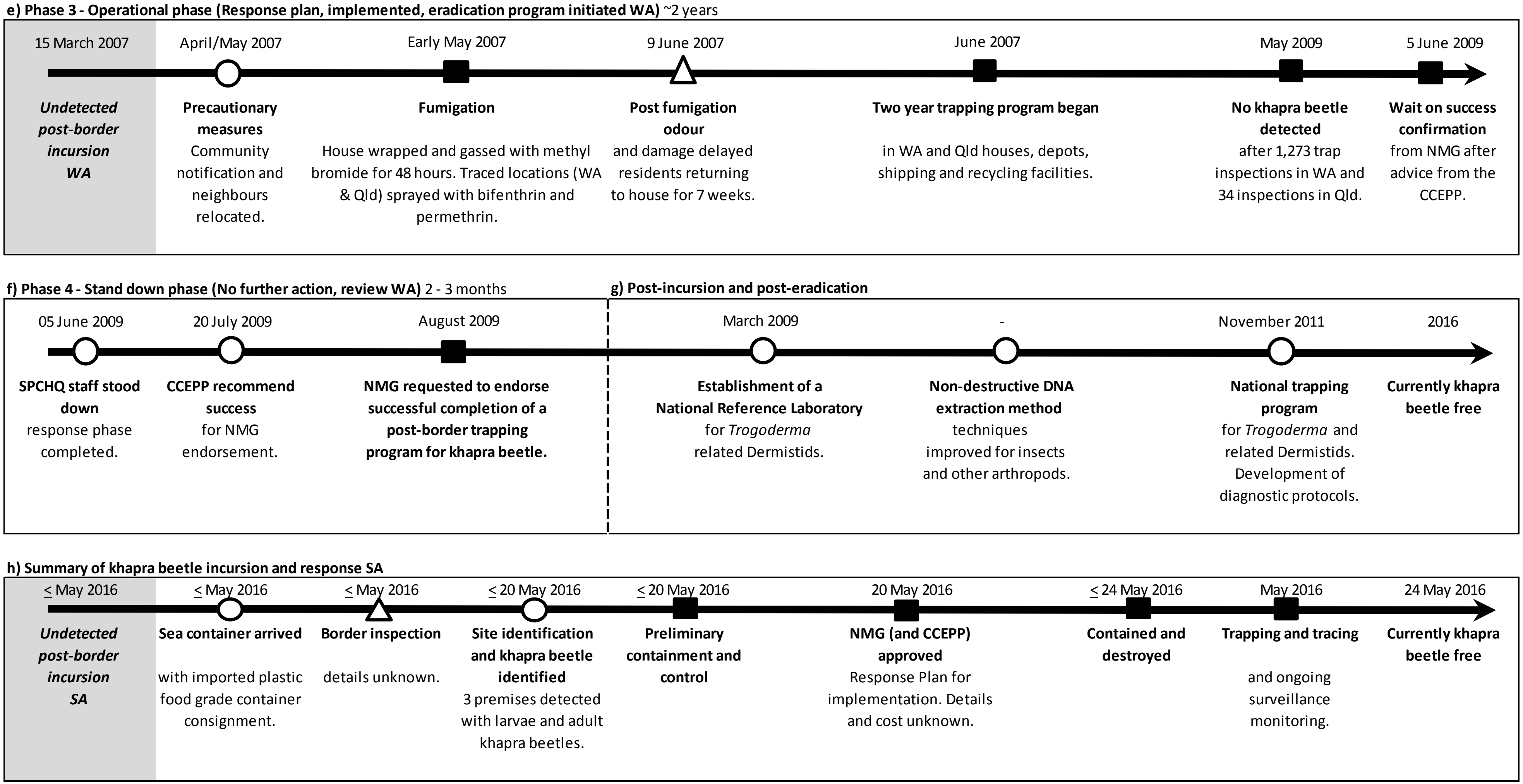

Figure 5. Timelines presenting Australia's preparedness and response to khapra beetle incursions.

a) Summarised illustration of Australia's preparedness, incursion, response and eradication phases for khapra beetle (*Trogoderma granarium*) during the period from 1998 through to 2016. Sources: DAFWA, 2009, 2007a; PHA, 2014; Rees and Banks, 1999

b) Developing reference material specific to khapra beetle and Australia in 1998 through to 2005 enabled rapid emergency response planning and implementation of the eradication program once an incursion was detected. Sources: Botha et al. 2005; Botha n.d.; DAFWA 2009; Rees and Banks 1999

c) Concise illustration of the entry, transfer, detection and tip off to authorities of khapra beetle in a house in Western Australia in 2007. Sources: DAFWA, 2009, 2007a

d) Critical stages in the response to the suspected and later verified incursion of khapra beetle into WA. Expert identification led to precautionary containment and fumigation whilst a second expert opinion was sought to confirm the pests' identity. The Emergency Response Plan was developed, endorsed and approved with minimal delay which enabled the implementation of the eradication plan as soon as possible. Sources: DAFWA, 2009, 2007a

e) Key actions executed as a part of the Emergency Response Plan for the khapra beetle incursion into WA. Actions included notification to the community surrounding the infested house, fumigation and a two year trapping program in two states. Sources: DAFWA, 2009, 2007a, 2007b

f) Eradication deemed successful and the emergency response program concludes. Source: DAFWA, 2009

g) Post-incursion and post-eradication activities such as the National *Trogoderma* trapping program, the development of a National Reference laboratory for *Trogoderma* related Dermistids and advances in non-destructive DNA extraction techniques for arthropod specimens continued until late 2011. The additional benefits of this work will be valued in future post-border incursions of *Trogoderma* species. Sources: Castalanelli et al., 2010; Cunningham, 2012; DAFWA, 2009

h) Concise summary of the recent khapra beetle post-border incursion and response in SA. Sources: DAWR, 2016c, 2016d

■ denote critical stages that contributed to the success of the eradication program ○ denote other noteworthy stages essential to achieve the critical points △ denote missed opportunities or unexpected incidences.