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COMMENTARY

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The eradication of pea weevil *Bruchus pisorum* (L.) (Coleoptera: Chrysomelidae) from New Zealand

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Abstract

Pea weevil (*Bruchus pisorum* (L.), Coleoptera, Chrysomelidae) is a major cosmopolitan pest of pea crops and is established in most pea growing areas of the world. Pea weevil has been detected several times in New Zealand, but these incidents never resulted in an established population. Establishment occurred in 2016, when pea weevil was detected in stored and field peas in the Wairarapa region of the North Island. After due consideration, including initial delimiting surveys and analysis of potential pathways, the Ministry for Primary Industries (MPI), in consultation with industry and community interests, decided to attempt eradication. The eradication programme utilised a range of tactics including a regionalised pea growing ban, movement restrictions for pea plant material, pea trap crops managed with insecticides and herbicides, and physical pea plant destruction to prevent regrowth. Trap crops played a dual role for local surveillance and beetle destruction. A national survey for pea weevil was also undertaken. The eradication programme was implemented under national New Zealand legislation (including a Controlled Area Notice) and an awareness raising media campaign. The initial pea weevil infestation was found over an area of approximately 115,000 ha. National surveillance resulted in no pea weevil detections outside of the Wairarapa Controlled Area. In the first year of the eradication programme (spring 2016–2017), the pea weevil population was reduced by 99.1%. Zero detections of pea weevil were found in the spring of 2018 and 2019, confirming eradication, and the planting ban and movement restrictions were lifted in 2020. This paper details what appears to be the first documented eradication of pea weevil anywhere in the world and explores the technical challenges, options, and tactics which eventually led to this successful eradication.

Keywords: Pea weevil, *Bruchus pisorum*, Eradication, Trap cropping, Controlled area, Growing ban

Introduction

Despite greater awareness of the impact of invasive species the processes of introductions of non-native species remain an unwelcomed consequence of escalating rates of international trade and travel (Meyerson and Reaser 2002). The rate at which alien species invade new regions continues to grow (Seebens et al. 2017) and for many of these invasive species, their establishment and geographical expansion is associated with a range of detrimental economic, environmental, and social consequences (Westphal et al. 2008). Many jurisdictions have instigated a range of actions, often layered across the invasion continuum, to prevent the establishment of invasive species or to mitigate their impact if they do establish. These may incorporate aspects of import standards, risk analysis, pathway risk management, surveillance, eradication, and if establishment cannot be prevented, long-term pest

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management will be considered. The Biosecurity Strategy for New Zealand (www.mpi.govt.nz), and The New Zealand Biosecurity System and how it operates and Kiwi Fruit Vine Health, (www.kvh.org.nz).

Management of invasion pathways to prevent establishment is often preferable, but eradication of newly established populations may be necessary, and for some species at least, this can be a successful and cost-effective undertaking (Liebhold et al. 2016). It is also important to document the success or otherwise of attempted eradication programmes so that lessons learnt can inform subsequent programmes at later dates or localities (Tobin et al. 2014; Smith et al. 2017; Kean et al. 2021). For some species (e.g., fruit fly, gypsy moth), eradication programmes may be well understood across the global biosecurity community, but for other invasive species (e.g., less commonly encountered or more difficult to eradicate), such as the pea weevil, this information may not be readily available to the biosecurity community.

The pea weevil, *Bruchus pisorum* (L.) (Coleoptera: Chrysomelidae), is a seed-feeding chrysomelid beetle and is not, as its common name would imply, a true weevil, but a bruchid beetle. It is thought to have originated from central Asia and has become a major pest of peas around the world, including the United States, Australia, Europe, Ethiopia, and parts of Asia (Reddy et al. 2018). Worldwide infestation levels of pea seeds range from 10 to 90%. In various parts of the United States Pacific Northwest, Burns and Briggs (2001) documented seed damage ranging from 42 to 82%. In South Australia, heavily infested pea crops may have up to 15–20% of pea seeds infested by pea weevil larvae. Infested seeds can lose up to 25% of their weight from larval feeding, are prone to shattering during harvest and germination, and seedling health is seriously affected (Baker 1998).

The biology and management of *B. pisorum* was recently reviewed by Reddy et al. (2018). *Bruchus pisorum* is a strictly monophagous pest of *Pisum sativum* L. (Fabales: Fabaceae). Adult females must feed on pollen from pea flowers to complete their ovarian development and egg production. A single female may lay between 100 to 700 eggs (Brindley and Chamberlin 1952) onto developing pea pods and flowers, usually in spring. The species is mostly univoltine, taking 50–80 days from oviposition to adult emergence. *Bruchus pisorum* adults will emerge from the seed after pupation is complete or stay within the seed until the following spring when conditions are suitable for emergence. Emergence can be prompted by the movement or vibration of seed associated with human activities (Armstrong 2005). Adults overwinter in hedgerow shrubbery, tree bark, fence posts and outbuildings adjacent to pea fields. From there adults re-colonise pea crops, particularly during flowering in spring. Some pea weevils may spend the winter as adults inside the seed, especially in cooler climates. They are capable flyers; Wakeland (1934) reported adults in autumn can fly up to 12 m above the ground in cultivated areas and travel up to 5 km to seek shelter in the bark of trees.

Peas are worth an estimated $120 M to the New Zealand economy (Aitkin and Warrington 2019). Their uses comprise vegetable varieties for (human) food consumption as peas (processed vegetable peas for domestic and export as frozen, freeze dried and canned product), seed for domestic and export use (process pea and dry pea production) and dry peas that are exported as whole dry grain for production of high-value snack food products in Japan and South East Asia. Peas are increasingly being used in forage and cover crop mixes to support animal-based industries and as components of feed grain mixes domestically. A rapidly expanding market is for the use of dry yellow peas for the production of plant-based food products. Peas are also an important rotational crop in New Zealand supporting cereal and other crop rotations by providing a break crop for disease management, fixing nitrogen and improving soil structure (Askin et al. 1985).

The pea weevil is listed as an Unwanted Organism under the New Zealand Biosecurity Act (1993) and listed as one of the major pest and disease threats to New Zealand (MPI 2022a). Until 2016, pea weevil had been detected several times in New Zealand but had failed to establish (Somerfield 1977, 1981, 1989). As far as we can determine there is no record for the eradication of pea weevil from any national, state, or regional authority. Here, we report on the detection of an established infestation of *B. pisorum* in the Wairarapa, New Zealand in 2016, and the technical aspects of the subsequent incursion response and successful eradication by 2020. We discuss the technical challenges, options, and tactics which eventually led to this successful eradication, to inform future responses to this and similar insect pests.

Methods

Initial detection and investigation

A report of a suspected finding of pea weevil was received by the Ministry for Primary Industries (MPI) in March 2016 through MPI's public Pest and Disease Hotline. Weevil adults were observed by a manager of a pea seed storage facility in the town of Masterton (Wairarapa, North Island, New Zealand; − 40.95°N, 175.66°E) in bulk seed storage bins that contained locally grown pea seed lines that had been recently harvested. A MPI Quarantine Inspector visited soon after, and observed a substantial population of adult pea weevils emerging from locally grown pea seed, providing direct evidence of infestation of pea weevil to the stored pea seed (i.e., it was not due to contamination). Samples of insects and infested seed were identified by MPI's Plant Health and Environment Laboratory (PHEL) as *Bruchus pisorum* (L.) (Coleoptera: Chrysomelidae) in early April 2016, with immature instars in the pea seed providing further direct evidence of pea weevil infestation of locally grown pea crops.

The specimens submitted to PHEL were determined to be from pea seed harvested from the Wairarapa area in the 2015–16 growing season. The source of the original pea seed that gave rise to these pea crops could not be fully determined but at least one seed consignment came from the USA in October 2015, where pea weevil is present. On further investigation, several additional seed lots (7 varieties and 14 lots) imported from North America in April 2015, were implicated as potential sources. In addition, unsown remnants from these imported seed lots that had been retained by the seed store were found to contain evidence of pea weevil infestation (adult pea weevil infested seed) in April 2016. Given an initial pea weevil infestation of pea seeds planted in October 2015, typical pea weevil population dynamics under ambient Wairarapa climate conditions experienced throughout 2015–16 (Metservice 2022) could lead to substantial population numbers at the end of the growing season.

The infested seed lots were determined to have been cleaned and supplied to several growers in the Wairarapa region through a local business involved in purchasing and selling pea seeds. MPI investigators traced sales of potentially infested seeds to 13 different properties and 3 seed depots that had received or had infested seed in storage. As a precaution, harvested pea seeds were sampled from an additional 20 pea growing sites from the total of 33 farms in the Wairarapa that had grown and harvested peas in 2016. Most of the potentially infested sites occurred within a 10 km radius of Masterton, but some were as far as 50 km away. The geographical extent of these sites suggested that the pea weevil was potentially widespread throughout the Wairarapa.

At this time, it was not known if pea weevil had spread to other pea growing regions of New Zealand, which was a realistic possibility given the trade in pea seed throughout the country. All remaining suspect pea seed from the Wairarapa was fumigated, but it took several weeks before seed that had originated from the Wairarapa could be traced and checked for pea weevil; no pea weevil was found.

Governance and decision-making

In New Zealand, the statutory authority for responding to biosecurity incursions is defined by the Biosecurity Act (1993). Several key groups were responsible for different aspects of the response (Table 1).

In April 2016, the response Governance Group (GG) notified primary industry groups of the incursion and a Technical Advisory Group (TAG) was formed comprising experts from MPI, the arable industry, Foundation for Arable Research, and Plant & Food Research scientists. The TAG initially considered what actions would be needed to contain the infestation and what further information would be needed to make a decision on whether to attempt eradication. Most pea production in the Wairarapa region is for seed to be sown in the major pea production province of Canterbury. Due

Table 1 The different groups involved the governance and operationalisation of the pea weevil response

Group	Responsibilities	Membership
MPI Incursion Investigation Team	Responded to the reported incursion as it occurred. Established the initial parameters of the incursion and reported to the Response Team and the Technical Advisory Group	A specialist team within MPI
Governance Group	Approval of strategy to eradicate	MPI and Industry (growers and seed companies)
Technical Advisory Group (TAG)	Provided expert advice on possible surveillance and eradication scenarios. Provided advice to the Response Team and to Industry. Designed specifications for surveillance including trap cropping	Expert representatives from MPI, industry and research
Response team	Provide management and resources for the eradication. Subcontracting operational requirements. Communication to industry and general public through various media outlets MPI Legal set specifications for the Controlled Area under the Biosecurity Act 1993	A specialist team within MPI, also includes contractors such as AsureQuality
Affected industries	Complied with regulations of the Controlled Area Notice, provided general awareness and reporting of pea weevil, pea crops and volunteer pea plants within the controlled area, and provided the facilitation of local information transfer	Pea growers, Federated Farmers, Foundation for Arable Research, Vegetable processers, garden supplies
Public	Complied by not growing peas and assisted by reporting any suspect pea weevil or wild pea plants, or pea straw	Masterton residents who were within 5 km of heavily infested farms

to the sizable population of pea weevil found in Wairarapa in the 2016–17 growing season, in the absence of a biosecurity response it is likely that the pest would soon spread through infested seed into Canterbury where it would be much more challenging to eradicate due to the amount of peas grown and the lack of geographical boundaries. Thus if eradication were to be attempted, it was important that it occurred before the pea weevil spread to Canterbury.

A series of meetings to inform and update local growers of the situation took place with initial contacts being made on 6 May 2016 (Masterton) and 12 June 2016 (Carterton). Similar meetings were later organised by Federated Farmers for growers in the South Island, beginning at Ashburton (mid-Canterbury) on 10 August 2016.

Meanwhile, the TAG developed several response options for the GG. The 'do nothing' option was rejected due to the high pest status of pea weevil. A 'contain and suppress' strategy would require growers to comply with certain conditions including foliage sprays, early harvest, field hygiene and post-harvest treatments. However, the TAG felt these measures would not provide 100% assurance as there are a number opportunities where pea weevil could survive and spread. Providing the spray timing is correct, populations can be controlled with repeated insecticide treatments which will reduce economic loss. Baker (1998), stated that even if the whole crop is sprayed with the best spray gear and under ideal conditions, some adults will survive, and the harvested seed will be contaminated. At best, and provided the spray timing is correct, this subdues the population to levels where there is less economic loss. The risk of infested crop and seed residues remaining in the ground post-harvest would need to be managed reasonably quickly to prevent weevils emerging from waste seed and finding hibernation sites until the following spring. Experience in North America, Australia and Europe suggests that pea weevil can be partly controlled by combining chemical and cultural practices, but populations prove to be resilient despite regular chemical control.

Two eradication options were presented. The first was a 'local ban' on pea growing and to establish trap crops at the infested sites and place a 10 km quarantine zone around each site within which growers would be encouraged to grow alternate crops. The other was a 'regionalised ban' (Controlled Area) on pea growing for 2 years and installation of spring trap crops which would be grown on suspected infested properties to draw in pea weevils and monitor the residual populations. This option was recommended by the TAG and also had the support of Federated Farmers who represented a large contingent of growers in the Wairarapa.

There were several reasons to decide on an eradication strategy. To control pea weevil on an ongoing basis with field-applied insecticides and post-harvest fumigation would add significant cost to the production of seed and peas grown for processing. Consideration was also given to pea growers in Canterbury where 70% of New Zealand's peas are grown, particularly peas for processing. A successful eradication would enable Wairarapa growers and seed companies to sell their pea seed to other regions who may not want to take that risk under a more managed approach. There is nil tolerance for pest contamination of peas for human consumption, namely the frozen pea market and novelty snacks both exported from New Zealand.

As more information became available on the extent of the infestation and the feasibility of eradication using the current tactics, a cost benefit analysis finalised on 16 June 2016 led the GG to decide to attempt the second eradication option using a regionalised ban. Most growers supported this decision and offered valuable cooperation and advice during virtual (Skype) and face-to-face meetings. The eradication plan was approved by the GG and planning began on 13 July 2016. The strategy involved establishment of a growing ban with a regional Controlled Area, use of trap crops, suction trapping, and pea straw management. A national detection survey was also endorsed in July of 2016 to determine whether pea weevil had established outside the Wairarapa. A key component of the strategy was a campaign to support local and national media and public awareness.

Controlled area notice

On 27 July 2016 a Controlled Area Notice (CAN) was implemented under the Biosecurity Act 1993. This prohibited the growing of peas for two years in an area of 750,000 ha, comprising around 88% of the Wairarapa region. It also restricted the movement of 'risk' goods (i.e. pea plants, pea seed, feed peas and pea straw) in and out of the Controlled Area. The ban on pea growing was exempted for specific trap crops (see below). The CAN was revised in April 2018, when the GG, in consultation with industry and with recommendations from the TAG, decided to continue the pea growing ban and movement restrictions for a further 2 years.

Amended import health standard

In response to the 2016 pea weevil incursion, MPI reviewed the specifications for imported pea seed with the result that commercial consignments required mandatory fumigation with phosphine or methyl bromide before biosecurity clearance could be given. As result of the review, phosphine treatment duration was also increased. However, most commercial consignments of imported pea seed now undergo methyl bromide fumigation on arrival to New Zealand. This treatment is quicker than phosphine which can now take up to 14 days to complete, (MPI 2022b). The seed is also subject to sampling and inspection by the Quarantine inspectors. With these measures in place the risk of live pea weevil crossing the border is considered low by the Ministry for Primary Industries. This is an important contribution because eradication efforts are wasted if the pest is likely to subsequently re-invade.

Trap crops

The pea weevil is strongly attracted to pea pollen and the volatiles that pea plants emit (Reddy et al. 2018). To monitor the pea weevil population during the ban and to prevent further spread, selected growers were asked to voluntarily grow trap crops on or near the suspected or known infested sites. Growers and/or contractors were paid for growing trap crops on their land according to strict specifications. MPI contracted a commercial company (AsureQuality) to oversee the sowing and sampling (sweep netting) of the trap crops and dispatching of pea weevil samples to PHEL. This work was well supported by the grower organisations, Foundation for Arable Research and Federated Farmers.

In year 1, trap crops consisted of three strips of different pea varieties, which was reduced to two strips in the second year because the flowering times overlapped for two of the initial three varieties sown. Each strip was 30–50 m long and 6–10 m wide, considered by the TAG to be of sufficient size for adult pea weevils to respond to and also convenient for seed drilling equipment. One strip was planted with an early-flowering pea variety, either 'Sherwood' or 'Ashton', having a first flower at the 9th node or 1160 heat units and a sowing rate of 250 kg/ha. The other strip was planted with a late variety, 'Prometheus', first flowering at the 16th node requiring 1600 heat units and sown at a rate of 230 kg/ha. When the third strip was present it was planted with 'Mr Big' 365 kg/ha. All seeds were purchased from Masterton Vegetable Seeds or Seeds and Cereals. The two main varieties provided a continuum of flowering for 2–3 weeks. Traditionally peas are sown in Wairarapa in October, weather and soil conditions permitting, with flowering around December; this was the target growing period for the trap crops. Some planting of additional trap crops was trialled in early January in year 1 but these failed to detect pea weevils, perhaps due to the 'attract and kill' efficiency of earlier trap crops, so these were discontinued for year 2 and 3.

A total of 13 trap crops were used in the 2016–17 growing season, 22 in 2017–18, 25 in 2018–19, and 15 trap crops in 2019–20. Trap crop locations were determined by modelling the relative risk of infestation from previous infested crops. This depended on proximity to each previous infestation, the level of each previous infestation, and land use. Trap crops were located to optimise detection across the map of relative risk. The cumulative benefit of additional trap crops was also estimated, and that plateaued after about 25 trap crops, indicating that more than this would add relatively little value. Full details of the trap crop optimisation model are given in the Additional file 1.

Armstrong (2005) considered the only effective way to determine if pea weevil is present in a crop is to monitor crop edges every 3–4 days from the start of flowering using a sweep-net. This method has also been used to measure economic damage thresholds in pea crops in the northwest United States (Blodgett 2006). Brindley and Chamberlin (1952) stated that pea weevils will only be present in a crop if temperatures have consistently been above the pea weevil flight threshold of 18 °C. Therefore, entire flowering trap crops were sampled with an insect sweep-net on three to four occasions over a period of 2 weeks, mostly during flowering stages, on fine days when temperatures reached a minimum of 18 °C. The entire sweep sample was securely packaged, labelled and sent as soon as possible by track-and-trace courier to MPI PHEL for pea weevil screening and identification.

Each cropping season, on completion of three to four sweep net inspections and before the pea pods became so advanced that the developing seed within the pod could become infested with newly hatched larvae, the trap crops were destroyed. The trap crops were sprayed with an insecticide, Karate® AI (250 g/L Lambda-Cyhalothrin), or Attack® AI (475 g/L Pirimphos and 25 g/L Permethrin) mixed with a herbicide, either Reglone® AI (200 g/L Diquat), or Round-up® AI (540 g/Litre glyphosate) to kill any pea weevils present and to desiccate the crops. As a final precaution, the plants in the plots were cut with a rotary mower to mitigate the risk that there were any intact pods available for weevil development and to prevent any pea plant regrowth. This work was either completed by growers or contractors under AsureQuality supervision.

Suction trapping

In year 2 (2017–18) a 2 m high suction trap was deployed on one of the infested properties for approximately 8 weeks spanning crop flowering and early podding. All specimens collected were sent to MPI PHEL for identification.

Pea straw management

Besides seeds, pea weevil can reside within pea straw. Seeds in pea straw might sprout and provide unmanaged host plants for pea weevil. In addition, pea straw is traded nationwide as a popular garden ground cover, but such movement could spread pea weevil out of the Controlled Area.

The management of potentially infested pea straw proved to be an expensive process, especially the treatment option of burning. Growers were given three options to mitigate potential movement of pea weevil in pea straw outside of the Controlled Area and to mitigate the risk of potential unmanaged pea plants growing from seed within the Controlled Area. First, growers could store the pea straw on farm within the Controlled Area for the duration of the CAN (4 years). Second, they could feed pea straw to livestock on farm within the Controlled Area, under AsureQuality supervision in accordance with the CAN. The final option given to growers was to destroy the pea straw, usually by burning. On the production of verified information by AsureQuality that the pea straw had been destroyed, owners were compensated.

National detection survey

A national detection survey was undertaken in 2016–17 and 2017–18 to determine if pea weevil had spread to other pea growing regions of New Zealand. Over 300 individual pea crops were sampled in late spring using sweep-nets, when pea crops were flowering (Fig. 1). The spring sampling was consistent with what had occurred in the Wairarapa except whole crops (cf. trap crops) were sampled during flowering with the sampling emphasis on the perimeter of the crop where higher numbers of pea weevil adults are more likely to occur (Armstrong 2005). On larger paddocks over 25 hectares, this would take AsureQuality field officers up to 1.5 h to complete. Any samples that were collected were securely packaged, labelled and sent as soon as possible by track-and-trace courier to MPI PHEL for pea weevil screening and identification. The sampling plan was designed to detect a 1% infestation of pea crops with 90% probability and 95% confidence. There were 1672 commercial pea paddocks grown in 2016–17 and 1272 in 2017–18 for processing, feed and seed peas. To give a 95% confidence that there were no pea weevils outside of the containment area—a minimum of 305 and 297—paddocks would need to be sampled for each year respectively. In addition, all pea feed and seed paddocks were required to undergo soak testing for pea weevil from a 5 kg representative sample taken from each pea paddock after harvest. Soak testing swells the pea and can often reveal stings more clearly than in dried peas and in some cases a faint, but slightly dark shadow can be detected under the seed coat which reveals the presence of larvae, pupae or adults (Somerfield 1989).

Media and public awareness

A media campaign was initiated by MPI once the CAN was applied. It was designed to deliver the key message of "Help us get rid of the pea weevil. Don't grow peas in the Wairarapa". This message was promulgated through advertising in local newspapers, online and on radio in the Wairarapa, specialist magazines advertising, regular media updates especially local media, social media including paid placement on Facebook, MPI NZ Biosecurity web page updates (https://www.biosecurity.govt.nz/biosecuritynz), industry updates, communications to nurseries through New Zealand Plant Producers Incorporated (NZPPI) industry channels, visits to all seed retailers (garden and commercial) in the Wairarapa area to emphasise the controls and deliver posters and pamphlets to distribute to customers, and strategically placed billboards at major roadways entering the Wairarapa. Growers and the general public were encouraged to report any suspect pea weevil or pea plants by ringing a direct-dial telephone hotline maintained by MPI.

Awareness of the eradication programme was increased in rural areas by communication within farmer networks (e.g., Federated Farmers, Foundation for Arable Research). Rural delivery mail providers and regional council workers were asked to look out for roadside pea plants and report them to the MPI hotline. Similarly, agronomists and farmers were asked to report volunteer pea plants. The farmers in the Wairarapa supported the pea growing ban, giving up pea growing contracts in the short term for potential long-term contract sustainability, and the Foundation for Arable Research provided technical advice for alternate commercial crops that could be grown instead of peas.

Results

Sweep-netting for pea weevil in the controlled area

In the first season that trap crops operated (2016–17 growing season), pea weevils were found at 10 of the 13 properties that had received suspected infested seeds (see above). A total of 1735 adult pea weevils were collected by sweep netting from these 10 infested sites. The following season (2017–18), 15 weevils were sampled from trap crops at only two of the 22 sites that were sampled (Fig. 2). No pea weevils were found in the 25 trap crops in 2018–19, or the 15 trap crops in the 2019–20 season. Most pea weevils were found in sweep net samples from trap crops during December, coinciding with the flowering of the early season varieties 'Sherwood' or 'Ashton'. No sampling was undertaken in November and

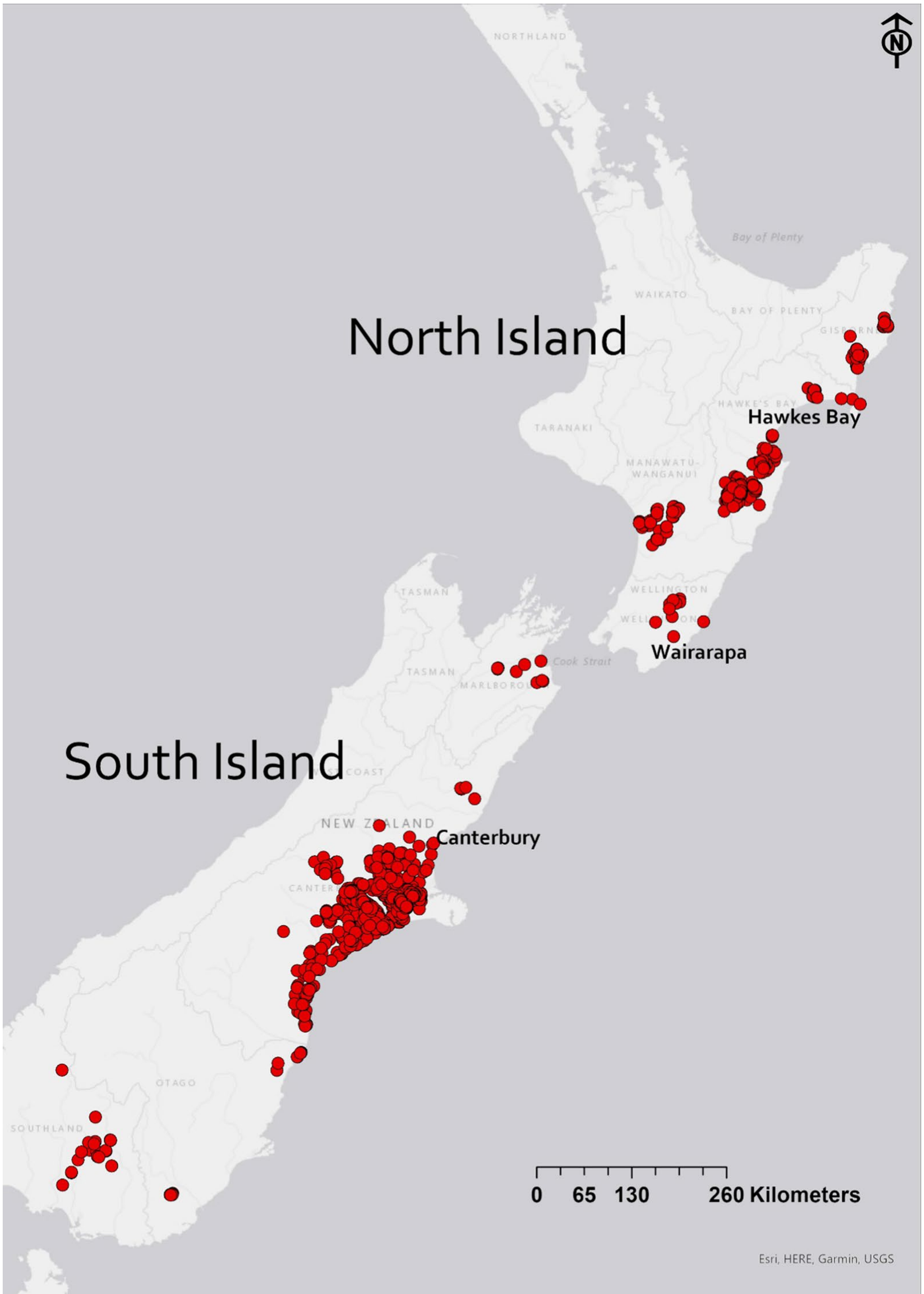

Fig. 1 Pea crops in New Zealand that were surveyed for pea weevil in 2016/17 and 2017/18

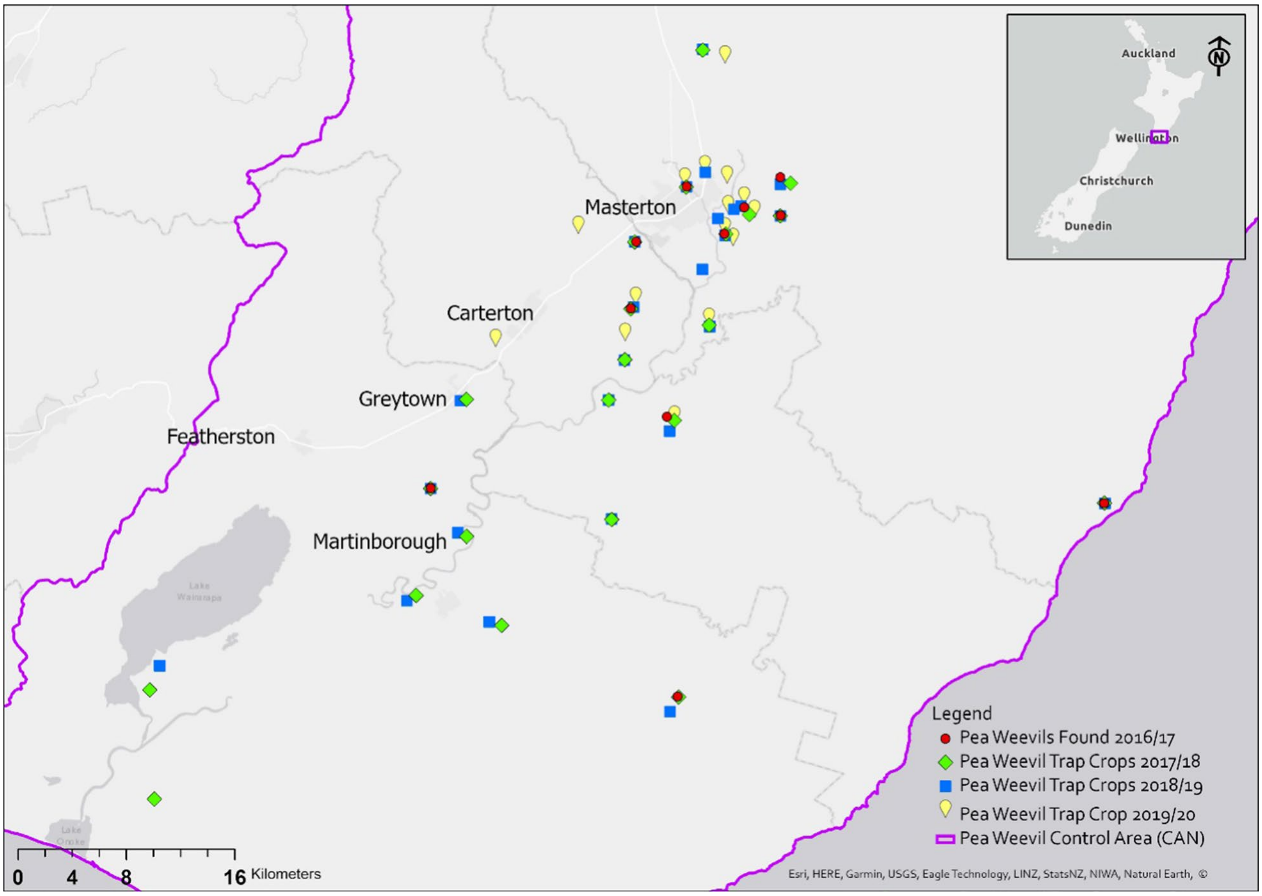

Fig. 2 Pea weevil trap crops and infested locations

very few pea weevils were found in the samples taken in January (Fig. 3). For the duration of the response, the earliest flowering for trap crops occurred in late November (2016) and the latest in early January (2017).

Suction trapping

The suction trap deployed in 2017–18 collected a wide variety of flying invertebrates, but no pea weevils. Due to the lack of detections and difficulties providing electricity for operating the suction trap in the remote areas of the trap crops, it was decided to discontinue the use as a surveillance tool after year 2.

National detection survey

No pea weevils were found from sweep-net or soak test samples of the pea crops spread throughout New Zealand and outside of the Controlled Area that were inspected for the two years of sampling (2016–17 and 2017–18) (Fig. 1).

In the two seasons 283 (2016–17) and 268 (2017–18) pea paddocks were each sampled three times with sweep netting during flowering. In addition to this, 643 (2016–17) and 565 (2017–18) paddocks of dried feed or seed peas were soak tested for pea weevil from a representative sample taken from each pea paddock.

Programme outcome

In February 2020, after two years of surveillance with no pea weevil detections, the ban on growing peas in the Wairarapa was lifted. As a precautionary measure, peas sown in the spring of 2020 that were within a 5 km radius of the most infested field during the first and second year of the eradication programme required sweep netting during flowering, and a post-harvest sampling and soak test. This surveillance yielded no further pea weevil finds. The eradication was mandated in April 2016 and the CAN lifted in February 2020. Regional restrictions had been in place for just under four years.

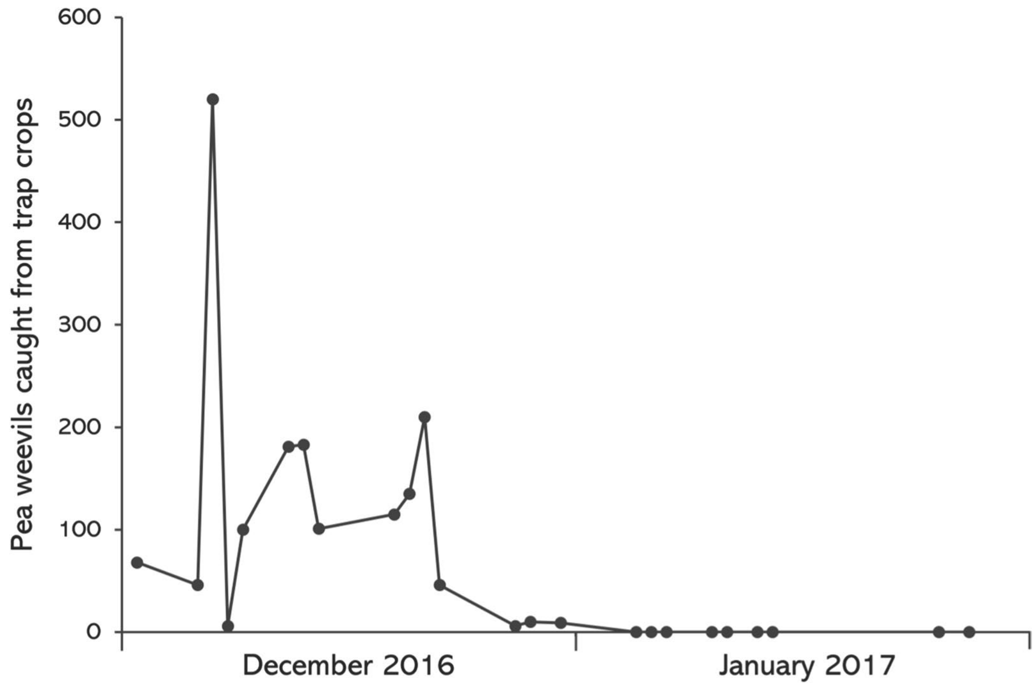

Fig. 3 Seasonal timing of pea weevil catches using sweep netting during the 2016–17 trap crop season

Discussion

This paper details what appears to be the first documented eradication of pea weevil anywhere in the world. Here we consider the characteristics of this invasion and the incursion response within the context of other successful insect eradication programmes.

New Zealand seed companies and pea breeders have been sourcing pea germplasm in an organised manner since the early 1900s, mostly from countries with known pea weevil occurrences because pea weevil is present in most temperate regions. The pea weevil has been regularly intercepted at New Zealand's border, especially during the 1970s and 1980s, but until 2016 there was no evidence that it had established beyond a growing season (Somerfield 1977, 1981, 1989; Archibald and Chalmers 1983). Since 2003, pea weevil was intercepted in pea seed at the New Zealand border on at least 40 occasions (Ministry for Primary Industries Laboratory Information System data 2021). The origin of these recent infested consignments was mainly North America, the source of most of New Zealand's recent pea seed imports, but also France, Italy, and Australia.

There are several factors that may have contributed to pea weevil's previous failure to establish in New Zealand despite the evidence of ongoing border pressure. First, imported pea seed has undergone inspection procedures at the border utilising International Seed Testing Association (ISTA) sampling methods (ISTA 2007) that ensure the residual risk of infestation and the infestation level are low. New Zealand's imported seed testing protocol is particularly rigorous, requiring five times the sample size mandated by the ISTA (MPI 2022c). Second, approximately 70% of the peas grown in Canterbury, New Zealand's main pea growing area, are harvested for human consumption, mainly for the frozen pea market (PGG Wrightson Seed Co unpublished data). Green pods are processed before any pea weevil larvae present would get a chance to pupate, so the risk of pea weevil spreading from harvested fresh peas is low. There is nil tolerance for such contamination in peas for human consumption, and impurities would be detected in the quality control system and destroyed. Third, peas have a relatively short growing season and a different second crop is often sown after cultivation. This lessens the chance of pea weevil remaining in crop residues or spilt seed. In addition, peas are not usually grown in the same field for 2 years in a row. This crop rotation, implemented primarily to manage disease risk, would also help prevent pea weevil populations from persisting. Finally, seed companies use established best practices and quality assurance systems to check contracted seed lines, using soak testing, for pea weevil and other pests. This ensures any infestation should be detected rapidly and was in fact how the 2016 Wairarapa incursion was found.

The success of the Wairarapa pea weevil eradication programme was probably predicated on several key factors, and it is informative to compare and contrast them to the key determinants of successful eradications for other insects. Probably the most comprehensive examination of successful insect eradications was carried out by Tobin et al. (2014) based on a database of 672 arthropod eradication programmes targeting 130 non-native arthropod species. The programmes were implemented in 91 countries between 1890 and 2010, and contained in the Global Eradication and Response Database (GERDA) (https://b3.net.nz/gerda/). They identified several characteristics of successful eradication programmes, only three of which seem relevant to the pea weevil eradication: taxonomic order, size of the infested area, and detectability of the target organism.

Tobin et al. (2014) found that the probability of successful eradication differed significantly among taxonomic orders. Lepidoptera (N = 115) and Diptera (N = 189) programmes, for which there were specific available control tools, attained 86.1 and 86.8%, success rate respectively. In contrast, only 71.4, 68.2, and 59.1% of programmes targeting Hymenoptera (N = 49 programmes), Hemiptera (N = 22), and Coleoptera (N = 88), respectively, were successful (Tobin et al. 2014). *Bruchus pisorum* (L.) is from the Order Coleoptera, which previous experience suggests would have a relatively low chance of success.

Another factor significantly correlated with eradication success was the size of the infested area, estimated as the maximum extent of the quarantine or movement control zone OR area treated OR the larger of the two. Tobin et al. (2014) estimated that the odds of a successful eradication programme were 1.3 times less for every log10 increase in area. For pea weevil, the Wairarapa Controlled Area was approximately 750,000 ha, suggesting a 50–80% likelihood of eradication success (Tobin et al. 2014, Fig. 3). However, the actual infested area was thought to be much smaller, at around 115,000 ha, giving a slightly greater chance of success.

The area infested was also found to predict the cost of eradication (Tobin et al. 2014). According to the model fitted by Tobin et al. (2014), eradication of the pea weevil infestation of 115,000 ha would be expected to cost around $10.5 M USD (in 2005 dollars), which is approximately $20.9 M NZD in 2021 (using the same conversions used by Tobin et al.). Interestingly, the operational cost of the Wairarapa pea weevil eradication was estimated to be only around a tenth of that at $2.02 M NZD, but additional funds totalling $5.3 M NZD were paid as ex gratia to growers who had to grow less profitable crops whilst the CAN was in place. The eradication cost was within the bounds of other examples with a similar infestation size (Kean et al. 2021).

Eradication programmes were estimated to be 8.1 times more likely to be successful if the target species was classified as having a high, rather than a low, detectability (Tobin et al. 2014); species classified as having a medium detectability were excluded from this analysis. The classification of species into high, medium or low detectability was somewhat subjective, but depended in part on the size and appearance of the insect as well as the availability of sensitive monitoring tools, such as traps baited with species-specific pheromones. The pea weevil is relatively small and unassuming, and cannot currently be detected with specific traps. However, its monophagy, attraction to pea flowers, and high detectability in seed samples mean that it can be found, if present. Sweep netting of flowering crops in the field and inspection of pea seeds in storage both proved to be relatively effective sampling methods for pea weevil. None were found in the (limited) suction trapping that was conducted, though there were likely to be few present in the area sampled.

Tobin et al. (2014) found significant correlations with eradication success for a range of other factors, but these are not likely to be informative for the pea weevil. For example, the primary feeding guild was also predictive of the probability of eradication success, but seed feeders like pea weevil were too few to be included in the analysis. The method of first detection was only a significant predictor of eradication success when the abundant data for *Lymantria dispar* and *Ceratitis capitata*, (ca. 19% of the dataset) were included. Similarly, polyphagous species were 6.2 times more likely to be eradicated than the combined group of oligophagous and monophagous species, but this result was potentially dependent on the dominance of polyphagous and easily eradicated *L. dispar* and *C. capitata* in the data. Pea weevil's host specificity was effectively exploited in the eradication programme through the use of a host ban (functionally equivalent to host removal), trap cropping for surveillance and what amounts to a 'lure and kill' tool. Indeed, Tobin et al. (2014) showed that host removal and destruction were most often associated with programmes against Coleoptera.

The data analysed by Tobin et al. (2014) did not suggest that voltinism, the number of generations per year, is an important determinant of eradication success. Nevertheless, the pea weevil's univoltine lifecycle and predictable seasonal timing of oviposition activity were important factors in its eradication. Pea weevil populations could only be effectively monitored once a year in December, when adults were active in flowering pea crops. The rest of the year, the pest was essentially invisible, hibernating in the surrounding environment or residing in pea seeds in the ground or in storage. In addition, the pest's univoltine life cycle meant that a relatively extended effort was needed to achieve and prove eradication. Continued commitment was needed across several years, both by the response teams but also by the growers and public of the Wairarapa.

There was some evidence of pea weevil survival into the second year as 15 weevils were detected at two sites within close proximity, one of which had very high number of weevils swept during the first year of trap crops. It is unknown if these are survivors from the first year or a new generation that had emerged from infested seed or more recently from pea straw or volunteer plants. Previous studies on the pea weevil (Zavitz and Lochhead 1903; Skaife 1918) found that a small proportion of adults may survive in seed for up to 2 years. We acknowledge that other factors could also account for the extended survival time in New Zealand, for instance volunteer pea plants and the ability for adults to survive on other plant pollens (Reddy et al. 2018).

A key contributor to the success of the pea weevil eradication, and one that was not captured in the data of Tobin et al. (2014), was the support and cooperation of affected local communities. Without the support of the growers and public of the Wairarapa it probably would not have been possible to eradicate this pest. The compliance in not growing commercial pea or garden pea crops and disposing of pea straw was especially important. Considerable effort was therefore warranted for MPI to gain the confidence and trust of these communities through involvement in community meetings which included representatives from support organisations. Industry bodies also played a key support role, for example Federated Farmers and Foundation for Arable Research advised growers on alternative crops during the pea growing ban. The combined contribution of the government, industry and communities working together was recognised as an important aspect of the successful eradication by New Zealand's Minister for Primary Industries Hon. Damien O'Connor. The biosecurity response to pea weevil in New Zealand has raised the awareness, and pea growers and agricultural contractors are now more familiar with this pest and more likely to report any suspect weevils to a free pest reporting hotline within New Zealand (MPI 2022d).

According to the determinants for eradication success suggested by the analysis of Tobin et al. (2014), pea weevil in the Wairarapa would not have been a particularly strong candidate for successful eradication. Tobin et al. acknowledge that their datasets were dominated by species such as gypsy moth and fruit flies which are routinely eradicated from new invasion sites, but pea weevil shares few characteristics with these species. The fact that pea weevil has now been eradicated does not so much question the conclusions of Tobin et al. (2014) and other similar analyses (e.g., Pluess et al. 2012a, b) as point to a deficiency in our assumption of what is possible. The GERDA database, analysed by Tobin et al. records cases where eradication was attempted, so is biased toward species like gypsy moths and fruit flies where we know eradication is relatively easily achieved. The successful pea weevil eradication, and the fact that it appears to have been the first attempt against this species, suggests our response to biological invasions in general may be somewhat conservative. Some authors have argued against eradication as a general tool for managing biological invasions (e.g., Myers et al. 1998, 2000) but the pea weevil experience encourages optimism for trying eradication against a wider range of target species, especially as our experience, expertise and response tools improve.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-022-00093-8.

Additional file 1: Optimising trap crop placement for detecting pea bruchid (Bruchus pisorum) in the Wairarapa. This supplement describes how the best placement was determined for trap crops grown in the 2017–18 season to detect pea bruchid, Bruchus pisorum (L.) (Coleoptera: Chrysomelidae) in the Wairarapa. Two scenarios were investigated, differing in whether or not the 2016-17 trap crops were repeated in 2017–18. Figures S4 and S5 show the risk map and locations for the first 25 trap crops as suggested by the model, and figure S6 shows how each successive trap crop contributed to the overall surveillance efficacy. After about 20 trap crops there was minimal difference in efficacy between the alternative strategies of re-using and enhancing the 2016–17 trap crops, and allocating all trap crops from scratch. Both strategies arrived at similar distributions of trap crops. Over all, the analysis suggested that any additional trap crops should be located in the highest risk zone.

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Author contributions
DV and RM were the main contributors to writing the manuscript and DT and JK placed the response in the context of the wider eradication literature. JK provided the modelling to inform the survey designs and undertook the research that is included in "The supplementary information: optimising placement of trap crops, 2017-18". DV, RM, AR, DG, IL, GB and DT were all members of the Technical Advisory Group making technical recommendations to the response. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the biosecurity response are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
During this work with plants and invasive species the New Zealand Biosecurity Act 1993 was adhered to and followed.

Consent for publication
This manuscript does not contain any personal information and all photos and maps were submitted by Rory MacLellan an author of the manuscript.

Competing interests
The authors declare that they have no competing interests.

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