Invasive Insects: Management Methods Explored

Gemma M. McLaughlin¹,³ and Peter K. Dearden¹,²

¹Department of Biochemistry, University of Otago, PO Box 56, Dunedin 9054, New Zealand, ²Genomics Aotearoa, University of Otago, PO Box 56, Dunedin 9054, New Zealand, and ³Corresponding author, e-mail: mclge271@student.otago.ac.nz

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Abstract

Invasive insect species can act as a plague across the globe, capable of vast expansion and rapid, proliferate reproduction. The spread of pathogens of serious diseases such as malaria and Zika virus and damages to agricultural crops number some of the afflictions invasive insects provide to humans alone. Additionally, an escape from predators can fail to keep invasive insects in check, providing potential threats such as extra resource competition to native species when insects invade. A variety of methods are employed to combat these invasive species, each with their own varying levels of success. Here, we explore the more traditional methods of invasive insect pest control, such as pesticides and biological control. In lieu of several unintended consequences resulting from such practices, we suggest some should be abandoned. We evaluate the potential of new techniques, in particular, those with a genetic component, regarding the costs, benefits and possible consequences of implementing them. And finally, we consider which techniques should be the focus of future research, if we truly wish to manage or even eradicate invasive insects in their introduced lands.

Key words: invasive insect, pesticide, biocontrol, gene editing, RNA interference

Many invasive species, introduced by humans to an environment where they would otherwise not exist naturally, thrive in such environments to the detriment of other, native species. Adverse impacts of invasive species can be ecological (such as the extinction of native species), environmental (where invasives contribute to changes in ecosystem function) and/or economic (for instance, damage to farmland or human health). Some invasions can eventuate in newly established pest species to an area, some of which are deadly to human health. For instance, the New World screwworm Cochliomyia hominivorax which invaded North America in the 1980s (Lindquist et al. 1992) literally consumes its host from the inside out, causing an excruciating death to livestock and human hosts alike. Insects are often versatile species, found in all types of environment, and are counted as a little over two-thirds of the known species in the animal kingdom. It is perhaps not surprising that they have proven to be immensely successful invaders.

Insect introductions, while largely unintended and human-driven, have resulted in particularly successful invasions, some spreading their populations across the globe. Once established, populations can become difficult to contain and/or manage. For example, the invasive ant species the Argentine ant Linepithema humile form ‘supercolonies’, that can range up to 6,000 kilometers and grossly outcompete native ant species (Human and Gordon 1996, Holway 1999, Giraud et al. 2002), while the red imported fire ant Solenopsis invicta is estimated to annually cost US$300 million in damages to livestock, human health, and wildlife to the state of Texas alone (Pimentel et al. 2005). Social wasps Vespula vulgaris and V. germanica reside at their highest densities in New Zealand—on the other side of the planet from their home range—at up to 40 nests per hectare, causing economic damages at US$90 million annually (Moller et al. 1991, MacIntyre and Hellstrom 2015). Mosquitoes particularly pose a significant threat to human life, as they can be vectors of several pathogens which can lead to the spread of disease. An estimated 216 million cases of malaria occurred globally in 2016 (WHO 2017), and the spread of Zika virus in the United States, where if pregnant women are infected, can result in infants with microcephaly (Mlakar et al. 2016). The pathogens of diseases such as dengue fever are also transported via mosquitoes. There are estimates of 390 million infections per year, with possibly up to 3.9 billion people at risk from infection (Brady et al. 2012, Bhatt et al. 2013). Damages to crops by insects can be insurmountable, with pollen beetles (Meligethes aeneus) targeting oilseed rape throughout Europe, even resulting in a 100% loss of the crop in Germany in 2006 (Slater et al. 2011). For more examples of notorious invasive insects, see Fig. 1.

Efforts at management of invasive insects to date often provide short-lived effects, thus requiring constant vigilance, which can be both costly and labor-intensive. Current methods are often non-species-specific, meaning the act of controlling a pest can be equally environmentally damaging as the pest itself. Here, we outline current methods used to combat invasive insects and evaluate their effectiveness. In light of a desire to tackle this issue, we explore the potential...
Invasions of nonnative species begin with an initial arrival (e.g., via international export such as lumber shipments), and may become established as a new population. Such populations may grow and spread over time, reaching pest densities and invasive status (Lodge et al. 2006). While new policies were implemented in the early 20th century to reduce the introduction of invasive pests, the United States now accumulates an average of ~2.5 nonnative fore insects per year (Aukema et al. 2010). New methods have emerged to detect and eliminate invasive insects before they reach invasive levels. Biosecurity New Zealand lists a number of potential invasive threats to the country on their website, highlighting what to be on the lookout for and how to report any new sightings. One research group set up two separate areas in China for sentinel plantings of Mediterranean European and temperate trees to test which potential Asian insect species may colonize European trees (Roques et al. 2015). A total of seven tree species were planted, with at least monthly visits over a 4-yr timespan where all seedlings were examined for the presence of phytophagous insects and/or damage. Seedlings were then beaten over a collecting sheet to collect any organisms present. This study resulted in a new list of potentially invasive Asian insect pests, with only 26% of insects collected identified to a species. While this study provided a novel method to detect potential invasive insects before establishment, it is a slow process spanning several years, with high labor intensity and cost. The authors themselves confessed the identification of insects at the species level was difficult and advocated for the development of molecular databases to better identify any discovered insects.

Initial Detection

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Chemical Pesticides

Pesticides are used globally to protect crops and humans from damages incurred by insect pests. While such treatments can be effective at reducing densities of invasive pest insects, pesticides include a range of toxic chemicals dispersed to the environment to target specific species. Such treatments can be extremely effective. When Volium Flexy (chlorantraniliprole and thiamethoxam) were applied to farmers’ field crops, mortality rates of the polyphagous pest Helicoverpa armigera rose to over 85%, improving tomato crop yield (Abbas et al. 2015), and the application of fipronil-laced bait stations reduced traffic of invasive social wasps by over 90% at several field stations in New Zealand (Edwards et al. 2017).

However, insecticides can also harm nontarget organisms to the detriment of the environment researchers are trying to protect. Rachel Carson’s Silent Spring (Carson 1962) exposed the reality of the insecticide DDT’s impact on public health and surrounding environment, and spurred on the creation of the Environmental Protection Agency in 1970 (Paull 2013). To this day, additional effects of DDT are being discovered, including the possibility of multigenerational, epigenetic obesity after ancestral exposure to this insecticide has been investigated (Skinner et al. 2013). To counter such issues, the development of selective insecticides aims to target specific species and eliminate nontarget effects. The bacteria Bacillus thuringiensis var. Kurstaki (Btk), or Foray 48B, was used as a spray
in Auckland and Hamilton, New Zealand, to counter the invasion of the painted apple moth _Teia anartoides_. Populations of these moths decreased to as little as 1% that of previous years. However, some areas with heavier vegetation cover had less success (Charles et al. 2005, Richardson et al. 2005). Transgenic _Bt_ cotton crops have also been used in India, China, South Africa, Mexico, and Argentina, to control some lepidopteran and coleopteran invasive insect pest species (Qaim 2009, Krishna and Qaim 2012). This is particularly encouraging, as _Bt_ can act as a nontoxic insecticide with a wide distribution.

Additionally, insects can develop resistances to pesticides, with resistance evolving as a heritable trait and spawning insecticide-resistant populations, marking such pesticides as useless. DDT, e.g., was implemented as a pesticide for mosquitoes in 1946; within a year of introduction, species _Aedes tritaeniorhynchus_ and _Aedes solicitans_—some of the major vectors of yellow and dengue fever—had cases of resistance (Brown 1986). Further incidents of resistance can also be found throughout the literature (e.g., Tabashnik et al. 1990, Zettler and Cuperus 1990, Hemingway and Ranson 2000).

Dosages can be increased to combat resistance, inevitably resulting in higher accumulations of insecticides in the environment, and the evolution of more effective resistance. Additionally, residues from pesticides used on crops can contaminate our foodstuffs and ultimately can be consumed by humans (Carvalho 2006). Another strategy includes the manufacturing of new chemicals for the market. This approach introduced neonicotinoids, literally ‘nicotine-like’ toxins to the foray. In the early 1990s, imidacloprid and thiabendox were introduced as a method of neonicotinoid insect pest control (Tomizawa and Casida 2011). These neurotoxic insecticides act systemically by being taken up by plants, primarily by the roots, and transported throughout the plant via xylemic and phloemic transport (Bromilow et al. 1990). These then interact with the nicotinic acetylcholine receptors (nAChRs) of the insect central nervous system, and can kill within minutes. As these binding sites differ from those in vertebrates, they provide selective toxicity to insects. However, the half-life of these chemicals in soil can be up to 6,900 d (Van der Suijs et al. 2013), and the effect of neonicotinoids on nontarget organisms can be devastating.

Pollinators, especially bees, appear to suffer greatly from neonicotinoid treatment. For example, bumblebees exposed to neonicotinoids provide fewer pollination services to apple trees, ironically lowering crop yield for farmers (Stanley et al. 2015), and there is now a proven causal link with corn seeds coated in neonicotinoids and mass bee death (Van der Suijs et al. 2013). Such findings have led to the ban of imidacloprid, clothianidin, and thiamethoxam on 29 May 2018 in Europe by the European Commission (EU 2018). An expected successor of neonicotinoids as they fade from popularity are sulfoxaflor-based insecticides; unfortunately, issues are also arising in regards to these alternative pesticides. Recently, sulfoxaflor has been found to produce a slew of sub-lethal effects in bumblebees _Bombus terrestris_, with sulfoxaflor-exposed colonies producing no queens and fewer workers than control groups (Siviter et al. 2018).

It appears that the more insecticides are scrutinized, the more negative effects on non-target organisms are discovered. Logically, it should follow that the use of chemical insecticides should be abolished, but realistically that outcome appears unlikely. If researchers are insisting on the continued use of pesticides for invasive insect control, each pesticide needs to be thoroughly investigated for nontarget effects under stronger policies for regulation and application.

**Biological Control**

Invasive insect species may thrive in a new environment because they now exist in a paradise devoid of their natural predators. Biological control, or biocontrol, tries to remedy this by importing an invasive pests’ natural predators in the hopes they will reduce invasive insect densities. This concept is nothing novel and has been implemented since ancient times, with records from around the tenth century of _Oecophylla_ ants being sold at markets in China for farmers to release as a form of citrus crop protection (Liu 1939). The first successful biological control experiment was documented in 1889 with Albert Koebele’s intentional release of Australian vedalia lady beetles _Rodolia cardinalis_ to control populations of the cottony cushion scale, _Icerya purchasi_. The resulting dramatic, almost overnight control of the crop pests supplied significant benefits for farmers affected by the scale insects and provided a strong case for using biocontrol as a means of invasive insect management (Calagione and Dourt 1989). And contemporarily, green lacewings (_Chrysopidae_) are widely used as a form of biocontrol to manage many insect pests in a range of areas, from farm crops to forests (Tauber et al. 2000, Yang et al. 2014). As a nontoxic and possibly species-specific alternative to pesticides, biocontrol has some appealing factors as a form of invasive insect management.

However, early records of biocontrol can be lacking, with Koebele himself only recording successful introductions (Swezey 1931). While there are records of successful employments of biological control, there are also myriad failures, some with staggering consequences for nontarget organisms. The predatory snail _Englina rosea_ was released to Hawaiian islands in an attempt to control the alien African Giant snail _Achatina fulica_. Instead, _E. rosea_ invaded native forests and is believed to have rendered several endemic species of snails extinct (Howarth 1991). Despite these findings, _E. rosea_ was later introduced to the French Polynesian island of Moorea, with similar consequences (Clarke et al. 1984). Further investigation revealed a behavioral plasticity in the snail, with it probing into aquatic habitats and also preying on populations of freshwater endemic snails (Kinzie 1992), proving it to be a greater threat than originally considered. Additionally, cane toads were introduced to Australia to control populations of sugar cane beetles. Such beetles reside at the top of cane stalks the toads cannot reach. Subsequently, the densities of cane toads exploded, with a still-expanding range long after their primary introduction in 1935 (Phillips et al. 2007, Kearney et al. 2008), and the development of new phenotypes such as longer leg length (Phillips et al. 2006). Biocontrol of invasive wasps in New Zealand by the parasitoid _Sphecopaga vespum burra vespum_ failed completely, possibly because the parasitoids chosen were imported from North America to control wasp populations that originated from Western Europe (Donovan and Read 1987, Lester et al. 2014).

Biocontrol of the Argentine stem weevil (_Listronotus bonariensis_) by the parasitoid _Microtous hyperoidea_ hints at evolution resistance in such systems. While initial introductions of the parasitoid in New Zealand reduced rates of pasture damage by 80–90% (McNeill et al. 2002), attack rates have since declined by 44% (Popay et al. 2011). This decline was not associated with abiotic conditions, and occurred simultaneously across the country, suggesting selection of resistant genotypes that existed at lower frequencies initially (Tomasetto et al. 2017).

There are many risks researchers take when they deliberately release foreign species into a new environment, regardless of the assumed good intentions. Even if a potential control agent is researched thoroughly, new behaviors may not be observed until
Sterile Insects

The development of recent genetic techniques to combat invasive pests has shown some promise so far. Targeting a species’ reproduction is often viewed as a more humane approach to managing an invasive population, with effects that do not inadvertently harm nontarget species in the same environment. The sterile male technique (SMT) involves the release of large numbers of sterile males (SMs) into a population. Females that mate with SMs will produce few or no offspring. If a high enough number of SMs are released and mated with, a reduction in population size will ensue in the next generation. The SM technique has existed for decades, with many applications. It has been particularly successful with managing populations of the New World screwworm and Aedes aegypti (Gemmell et al. 2004). Since mtDNA is typically maternally inherited, male-specific mutations should not be selected against in the female germ line, despite a fitness cost to males (Beekman et al. 2014), making this a multi-generational tactic. This technique could prove successful after only a single release of female insects carrying the TFT mutation, providing a more cost-effective and less labor intense avenue (Gemmell et al. 2013). Proof of concept experiments have been conducted, but with only moderate observed decreases in affected Drosophila populations compared to controls, but with differences maintained over a trial period of ten generations (Wolff et al. 2017). The TFT also does not use genetic modification of the pest organism in question, thus avoiding the ethical issues and debates that ensue using such practices. While this genetic method has potential to tackle invasive insect populations with a smaller price tag, more research needs to be conducted to establish how successful this method would be across the insect class, especially in insects with a haplodiploid sex-determination system.

Using the maternally inherited, intracellular bacteria Wolbachia is also being considered for altering insect reproduction. Wolbachia occur naturally in myriad invertebrate species, and have been found to alter reproduction in mosquitoes. Acting as a form of cytoplasmic incompatibility (CI), uninfected females mated to Wolbachia infected males produce embryos that fail to hatch. This finding has been observed several times in Aedes mosquito species (McMeniman and O’Neill 2010, Yeap et al. 2011, Suh et al. 2017), holding potential to control insect pests that are vectors of pathogens of disease. Infected male mosquitoes are available commercially in the Florida Keys to combat the tiger mosquito A. albopictus, with weekly releases being conducted in client’s backyards. Researchers aim to have this strain registered by the Environmental Protection Agency as an approved ‘pesticide’ and eventually made available across the United States (Dobson, unpublished). The World Mosquito Program has demonstrated that strains of Wolbachia can establish and maintain itself in isolated populations of Ae. aegypti around the city of Cairns in Australia (Hoffmann et al. 2011, 2014) and has also been successfully deployed in the larger Australian city of Townsville, with no local dengue transmission detected after 13 yr of continuous transmission (O’Neill et al. 2018). This option ticks many boxes in what would make a suitable method for insect pest control, and the potential of Wolbachia as an agent of CI for other invasive insect pest species should be explored.

RNA Interference

RNA interference (RNAi) is a genetic method that targets a specific organism. RNAi is the process of using exogenous double-stranded RNAs (dsRNA) to target specific messenger RNAs (mRNAs) for degradation, which result in silencing the gene’s expression (Zamore 2001). Using RNAi for insect pest control would require the implementation of systemic RNAi, where the selected gene in the cell exposed to the dsRNA is silenced in addition to neighboring cells. Neighboring cells are affected due to dsRNA and dsRNA-derived silencing signals spreading via dsRNA-transporting channels (In C. elegans, systemic spread of RNAi is ideal for dsRNA molecules >50 bp long; Feinberg and Hunter 2003). An environmental response would be used, where the dsRNA is taken up from the environment surrounding the cell and silencing occurs in all cells that have taken up the dsRNA (Whangbo and Hunter 2008, Huvenne and Smagghe 2010).

The specificity of RNAi makes it a desirable tool for insect pest management, reducing the chances of spreading its toxicity to other nontarget organisms in the wild. The most common methods used
to deliver RNAi ingestion by insects via systemic endocytosis are microinjection and feeding. Microinjection was first implemented successfully in *Drosophila* embryos to knockdown frizzled-2 genes, resulting in defects mimicking loss of wingless function (Kennerdell and Carthew 1998). While microinjection has proven successful in several laboratory studies for insect control (Travanty et al. 2004, Boisson et al. 2006, Mutti et al. 2006), this technique would be difficult to implement in field experiments. Oral ingestion is a less invasive method, with the potential to be employed in field experiments. Feeding insects transgenic plants containing dsRNA has proven a useful method of pest control for crop protection against the western corn rootworm (*Diabrotica virgifera virgifera*, Baum et al. 2007), and a dsRNA enriched diet is proven to be a successful pest control of the pea aphid *Acyrthosiphon pisum*, regardless of life stage (Mao and Zeng 2012). However, RNAi via feeding can fail due to a low concentration of the dsRNA reaching the gut epithelium.

While RNAi is a promising tool for insect pest control, there are some limitations that may make it unfeasible for use beyond laboratory conditions in invasive wasps. For instance, natural populations of a pest insect can potentially have higher genetic variability than lab-reared populations, which could result in more variable results in field trials (Scott et al. 2013). Additionally, while proven successful, the application of dsRNA via microinjection out rules it as a means for RNAi delivery in a wasps’ natural environment. To date, it is unknown in insects proven sensitive to RNAi whether resistant individuals exist, and if so at what frequencies. Under selection pressure, such resistant individuals would flourish under RNAi conditions, possibly leading to fixation and rendering RNAi efforts deficient, similar to myxomatosis efforts to control rabbits in Australia (Anderson and May 1982). Furthermore, while feeding appears to be the most feasible application of dsRNA in wild populations, high amounts of dsRNA are needed to observe noticeable gene silencing and toxic effects in some orders such as Lepidoptera (Swevers and Smagghe 2012); such concentrations of dsRNA may not be possible to administer in nature where other dietary options will also be available. While RNAi as a method for insect pest control should be considered, further study considering the stability of dsRNA and effectiveness in field trials is needed.

### Gene Drives

A gene drive operates by hijacking the expected 50% Mendelian inheritance of a gene, propelling a desired gene through a population and showing expression in all of an individuals’ offspring, instead of only half (Fig. 2). This process can be orchestrated with the use of homing endonuclease genes (HEGs), which act as parasitic or selfish genes, capable of spreading throughout a population (Chevailler and Stoddard 2001, Burt 2003). Such selfish genetic elements do occur naturally (e.g., Raju 1994, Beeman and Friesen 1999, Schimenti 2000, Larracuente and Presgraves 2012), but have been difficult to engineer in the laboratory. However, the fairly recent discovery of CRISPR (clustered regularly interspaced short palindromic repeats) has provided a new weapon that could be employed to design gene drives in the lab.

Type II CRISPR operates naturally in bacteria as a form of immunity from invading viruses and plasmids (Doudna and Charpentier 2014). CRISPR has been investigated most in *Streptococcus pyogenes*, and essentially acts as a pair of scissors, creating a double-stranded break (DSB) endogenously within a DNA double helix. The break will then be repaired by one of two pathways: non-homologous end joining (NHEJ) or homology-directed repair (HDR). NHEJ fuses the damaged DNA strands back together using a nuclease, polymerases and a ligase, which often results in losses and additions of nucleotides (i.e., indel mutations) at the site of the DSB (Lieber 2010). HDR operates by using a native (or engineered) DNA template to replace the targeted gene with an alternative by recombination (Barrangou and Doudna 2016). These processes essentially equip researchers with the opportunity to pick and choose which trait/s to remove from a population, or provides the potential to incorporate desired sequences into an individual’s genetic code.

Compared to the more costly and less site-specific predecessors of genome editing, CRISPR/Cas9 mediated methods have been hailed as ‘a molecular scalpel where crude and unwieldy shears (zinc fingers and TALENs) were hitherto the cutting edge’ (Carroll and Zhou 2017). The use of the CRISPR/Cas9 system holds great promise, and should be considered as a new genetic tool for pest insect control. CRISPR has already been researched in *Drosophila* many times (see

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**Fig. 2.** (a) In typical Mendelian inheritance, an individual carrying a sex-linked dominant mutation will pass such a mutation on to, and therefore be expressed in, half of their offspring. In a gene drive system, however (b), the selected gene has the potential to be inherited by all offspring. A CRISPR cassette containing a guide RNA guides the Cas9 protein to the desired site to create a DSB. The cassette is inserted into the break while the strands anneal together, a process known as HDR. With the presence of a germline promoter, this gene-editing results in all-female offspring carrying the mutation, which has the potential to act as an effective method for invasive insect control.
Table 1. A summary of the discussed insect pest control methods, highlighting certain aspects of each

| Method                | Multi-generational effects? | Genetic modification? | Species specific? | Few applications needed? | Low labor intensity? | Cost-effective? |
|-----------------------|-----------------------------|-----------------------|-------------------|-------------------------|----------------------|-----------------|
| Initial detection     | No                          | No                    | No                | No                      | No                   | No              |
| Biocontrol            | Yes                         | No                    | No                | Yes                     | Yes                  | Yes             |
| Pesticides            | No                          | No                    | No                | No                      | Yes                  | No              |
| Sterile insects       | Yes                         | Yes                   | Yes               | No                      | No                   | No              |
| RIDL                  | Yes                         | Yes                   | Yes               | No                      | No                   | ?               |
| Cytoplasmic incompatibility | Yes                     | No                    | Yes               | Yes                     | No                   | No              |
| Trojan females        | Yes                         | No                    | Yes               | Yes                     | Yes                  | Yes             |
| RNAi                  | No                          | No                    | Yes               | No                      | Yes                  | No              |
| Gene drives           | Yes                         | Yes                   | Yes               | Yes                     | Yes                  | Yes             |

Bassett et al. 2013; Gratz et al. 2013, 2014; Yu et al. 2013; Bassett and Liu 2014; Gantz and Bier 2015), and has even been used in eusocial species with haplodiploidy inheritance (Yan et al. 2017). However, as CRISPR functions as a form of genetic modification acting across multiple generations, thorough investigating and heavy regulations need to be put in place before field trials are even considered.

Using genetically modified organisms for any form of research can be met with polarizing emotions and strong opposition from local communities. And admittedly, the use of gene drives via CRISPR technology is something that could potentially have far-reaching consequences beyond the desired outcomes. The capacity of a gene drive to ‘escape’ its targeted population, and expand until it reaches global fixation (which would result in extinction in some cases) is possibly the greatest reason to ban the release of such GMOs. The agricultural giant Monsanto has been granted the license to use CRISPR to modify crops. However, they are barred from using it as a form of gene drive (Begley 2016). Additionally, other issues have been shown to arise when using CRISPR as a form of gene drive, such as resistance allele formation (Champer et al. 2017), a decrease in efficacy in inbred populations, and natural variation in wild populations could counteract CRISPR efforts (Zentner and Wade 2017).

One possible tool for overcoming accidental release of a gene drive could reside in the use of daisy drives, where each drive component is separated into a linear chain, and must be present in order for the drive to propagate itself (Noble et al. 2019). The daisy element at the base of the chain does not drive and is lost in half of the offspring, thereby stripping subsequent elements of the inheritance advantage a gene drive provides (Noble et al. 2019). Multiple daisy elements target the same allele and cause it to drive; this way the number of organisms carrying the drive elements halve every generation when mated with wild types, ultimately ceasing the drive over time (Min et al. 2017a). Quorum daisy drives go one step further, by harnessing underdominance whereby homozygotes are more fit than heterozygotes. For instance, organisms carrying a drive would need the selected elements to be haploinsufficient, that is, both required for viability. When mated with wild types, half of the offspring would be inviable. If both versions of homozygotes are equally fit, the more abundant version will be able to access complementary mates more, produce more offspring, and eventually reach fixation at the local population level (Min et al. 2017b). By using underdominance for local populations, ‘escaped’ individuals would not thrive in new environments, lacking mates with the same offspring to produce high numbers of offspring carrying the drive elements.

However, some researchers believe that the use of gene drives for insect pest control should only be implemented for insects that are causing humans grief, such as vector-borne malaria mosquitoes or schistosomiasis (Eswell and Gemmell 2017). We find this to be a very anthropocentric attitude, which values the life of a single species (in this case, us) over the myriad species that suffer, face extinction or are already extinct as a result of invasive species. If this technology is used to save human lives, it should also be employed to control insect pest species that threaten the existence of endangered species and/or native species. The threatened native species of the world would surely benefit more from research into eliminating their predators (and arguably, the elimination could be limited to certain rather than global ranges) than the removal of certain mosquito species, and deserve a voice in this debate. Similar sentiments regarding the use of gene drives are echoed by other researchers considering New Zealand biota (Dearden et al. 2017).

Ideally, long before an insect gene drive is released into the wild, several boxes need to be ticked. Firstly, a successful gene drive must be proven in laboratory conditions. Secondly, modeling experiments should be undertaken to estimate the appropriate number of individuals needed for release to quell an estimated population size. Thirdly, initial gene drive releases should be undertaken at isolated locations such as small remote islands, reducing the chance of escape beyond local populations. The addition of a daisy drive as a safeguard against escapes would not go amiss also. And finally, none of this can be undertaken without providing full disclosure to the general public, providing multiple outreach opportunities where individuals can express their concerns and be well informed of the processes and intentions of the researchers.

Concluding Remarks

While many options are available or in the works to control the numerous issues insect pests bring, none of them act solely as a silver bullet. A brief comparison of the methods discussed here are shown in Table 1. Ultimately, invasive insect pests are succeeding globally to the detriment of humans, their environments and many native species that reside in them. Current methods are proving costly and can be damaging to the environments and species researchers are trying to protect. Such methods should not be discounted as futile and have made a contribution, but are bordering on outdated in the wake of new techniques on the horizon. Novel genetic techniques are in their infancy, and it will be years before researchers have fine-tuned most of these techniques to the point of safe field experiments. However, these new promising technologies appeal on many levels, especially in that they are developed to target specific species and may dispose of populations in a more humane manner. We could be on the cusp of discovering some truly ground-breaking technology, several that have the potential to save the lives of many, help economies globally and/or pull back certain species on the brink of extinction. Now is
the time to seriously investigate the viability of what is possible, and embrace the most effective methods accordingly.

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