Chapter 5[1]: Management; Challenges, Opportunities and Lessons learned

Supplementary materials

[1] This is the final text version of the supplementary material of Chapter 5 of the IPBES Thematic Assessment Report on Invasive Alien Species and their Control (https://doi.org/10.5281/zenodo.7430682)

Supplementary material 5.1. Characterization of invasive alien species management by Indigenous Peoples and local communities

Supplement to **sections 5.2.1, 5.3.1.2** and **5.6.1.1**

Results of characterization of invasive alien species management by Indigenous Peoples and local communities based on 76 case studies (**Table SM.5.1**). Focus of management, ecosystems where management was conducted, managed taxa and motives for management were shown with the frequency of mention, frequency of percentages and percentage of cases reporting in parentheses. The case studies used for the characterization are a subset of studies on invasive alien species and Indigenous Peoples and local communities.[2]

Table SM.5.1. Characterization of invasive alien species management by Indigenous Peoples and local communities based on 76 case studies.

	Freq.	Freq. %	% Cases reporting
Management focus (n of cases = 76)	80	100.0	
Species	59	73.8	77.6
Pathway	2	2.5	2.6
Site	5	6.3	6.6
Ecosystem	4	5.0	5.3
Species X Site	10	12.5	13.2
Ecosystems where management was conducted (n of cases = 76)	76	100.0	
Terrestrial	64	84.2	84.2
Freshwater	10	13.2	13.2
Marine	2	2.6	2.6
Managed taxa (n of cases = 76)	120	100.0	
Animals (mammals, birds, reptiles, amphibians)	17	14.2	22.4
Fish (including crustacean)	13	10.8	17.1
Invertebrates	1	0.8	1.3
Insects	17	14.2	22.4
Plants	68	56.7	89.5
Fungi	2	1.7	2.6
Pathogen	2	1.7	2.6
Motives for management (n of cases = 71)	115	100.0	
Nature conservation	17	14.8	23.9
Improvement or protection of good quality of life			
Protect crop production	32	27.8	45.1
Protect livestock production	8	7.0	11.3

[2] Data management report available at: https://doi.org/10.5281/zenodo.5760266

Protect fishery production	1	0.9	1.4
Cultural or spiritual reasons	15	13.0	21.1
Protect resource use	17	14.8	23.9
Protect human health	4	3.5	5.6
Protect access or mobility	3	2.6	4.2
Protect Infrastructure	2	1.7	2.8
Obtain financial return (through getting jobs, business opportunities)	12	10.4	16.9
No active motives			
Following legislative requirements	4	3.5	5.6

Supplementary material 5.2. Pathway surveillance tools and technologies

Supplement to **section 5.4.2.1**

Sensor networks and smart traps - Recent growth in personal mobile computing has led to improvements in size and energy efficiency of electronic sensor devices, enabling their deployment on small-sized animals. Dubbed "One Giant Leap for Wildlife Tracking", lightweight telemetric tags have been deployed on hummingbirds, pigeons, toucans, and flying foxes. Miniature inertial measurement units, microphones, or weather sensors can be used to classify animal activities. Urination/defecation can be detected which can then be used to provide cues as to the shedding of a virus or seed dispersal, informing spatial predictive disease models. While most satellite trackers are still quite bulky, with a minimal weight of about 5g, smaller radio-frequency identification devices that weigh from 0.2g to 1g have been used to track insects such as bees, beetles, and dragonflies. Until recently, wireless sensor networks were limited to Wi-Fi or Bluetooth connectivity, restricting the range in which data could be collected (usually between 100 m and 1km). Examples of long-range systems have been developed in the context of Internet of Things (IoT) applications. Inexpensive off-the-shelf systems promise connectivity of 10 km, meaning that only a few base-station nodes would be required to collect data from most properties. An ongoing development includes battery life and robust casings are major considerations. Real time data processing algorithms to autonomously inform decision-making are generally developed for bespoke applications and are increasingly including machine learning and Artificial Intelligence. Lack of investment in digital information and communication technology (ICT, see glossary) connectivity infrastructure in remote and rural areas where properties or natural assets are generally large is a constraint, however, soon to be launched networks of low orbital communication satellites may bring broad band connectively to the entire globe.

Environmental Deoxyribonucleic Acid (eDNA) can be used to identify fish fry imported for the pet trade, or to monitor invasive aquatic species in rivers, ports or ballast water. The development of eDNA-based approaches for environmental and ecosystem applications has accelerated in recent years, and there have been a number of applications reported for the analysis of pests or invasive alien species, mostly for aquatic species due to the ease of sample acquisition and processing, including assessment of bivalve infestation with *Dreissena polymorpha* (zebra mussel; Peñarrubia et al., 2016), the invasive *Orconectes rusticus* (rusty crayfish; Dougherty et al., 2016), and invasive mosquitoes (Schneider et al., 2016). eDNA can be coupled to unmanned platforms and to automate analyses. Samples can be obtained from the broader environment, or from places such as run-off water, animal paths or the filtrate of air sacks. The only material constraint to the use of eDNA analysis may be the development of the required Polymerase Chain Reaction (PCR) for targeted sequencing or high-throughput DNA sequencing (HTS). There can also be complexity in respect of standardizing the sampling strategy, such that the sensitivity and specificity of eDNA analysis can be compared benchmarked with existing methods. This could limit the sensitivity of detection, although an increasing number of optimized sampling methodologies are being published (for example, Furlan et al., 2016). Metabarcodes are the next step to condense many geographically or temporally separated samples analysed for the same content adding power to an eDNA approach (Yamamoto et al., 2017).

Sentinel surveillance and monitoring - Sentinel alien plants (mainly trees) are similarly used for detecting invasive alien insects, nematodes and plant diseases. Sentinel plants used for surveillance assume that a risk of an invasive alien species has been identified and possible entry and dispersal pathways determined, and host ranges are well known. Sentinel plants are used either exotic in key locations (e.g., ports of entry) in the country that has identified the risk of invasion or native plants used and planted overseas to see what novel exotic alien pests and diseases are attracted to them (reviewed by Mansfield et al., 2019). Roques et al. (2015) described how sentinel European trees were planted in China during 2007-2011 as early warning of the invasive potential and likely impacts of Asian invertebrates that could colonize European trees should they arrive in Europe. Of more than 100 insect species, mostly defoliators, observed on five genera of tree hosts, at least six species were capable of larval development. This approach is being developed globally into an international plant sentinel network focused on linking botanic gardens and arboreta, National Plant Protection Organizations.[3] In a different example, *Merops ornatus* (Australian bee eater) was used to monitor the presence of alien honeybees (for example, *Apis cerana* (Asian honeybee)) by the analysis of scats at roost sites (Bellis & Profke, 2003). Sentinel beehives of *Apis mellifera* (European honeybee) are also strategically placed in ports and other points of entry in Australia for early detection of varroa mites. Wild caught honey bees have also been used to carry out surveillance of plant pathogens both known and not previously recorded (Roberts et al., 2018). It has also been suggested that managed honeybee colonies equipped with pollen traps could be used as a surveillance method for invasive plant species, given this is already an approach for understanding the source plants for honey bee pollen collection (Roberts et al., 2018).

Acronyms

DNA	Deoxyribonucleic Acid
HTS	high-throughput sequencing
PCR	Polymerase Chain Reaction

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Supplementary material 5.3. Species-based surveillance, detection and diagnostics tools and technologies

Supplement to **section 5.4.2.2**

Earth observation – remote sensing detection - Key advantages of remote surveillance over on-ground visual inspections include the larger coverage, the ability to use a range of spatial scales, repeatability and transferability of the procedure, the increased penetration of inaccessible areas, and the generally lower cost compared to the field teams (Jurdak et al., 2015). Some options for customizing the process to a particular application include the development of targeted application-specific sensors and sensing workflow, the development of specific and powerful algorithms based on, for instance, object recognition using machine learning or artificial intelligence for sampling specific targets and contexts, and data analytics to enable rapid (in some cases, real-time) generation of usable information. The data security and privacy issues still need to be resolved for many sensor network systems. Remote sensing can target specific invasive alien species directly using a specific optical signature or can detect their presence indirectly through methods such as suitable habitats or change in a landscape parameter over time (for example, where a weed is spreading, or a pest is feeding on vegetation). Invasive alien plants can be detected from their novel structure or phenology compared to native vegetation (Huang & Asner, 2009), or fast growth rate (rate of vegetation change over multi-date assessment; Diao & Wang, 2016). Less distinct species might be detected only at particular phenological stage(s) when they differ enough from their surrounding (Huang & Asner, 2009; Müllerová et al., 2017; Somodi et al., 2012). The detection and mapping of cryptic or low-density invasive alien species in complex landscapes may be difficult – in particular, when large areas need to be assessed. As fast-growing species, invasive alien species (especially herbs) can also be detected using a series of canopy height models throughout the season, generated either from light detection and ranging or photogrammetry (Structure from Motion algorithm; (Westoby et al., 2012), being especially true for herb species that show seasonal cycle (Martin et al., 2018).

Volatile detection technologies - The use of volatile detection technologies to detect a range of invasive alien species targets represent as genuine commercial opportunities, and could change the economics, practice and success of port-of-entry invasive alien species, surveillance and pest or disease control and eradication. The principle technical constraints are the identification of a unique volatile signature for each intended target, the ability to develop sensors that are sensitive enough to detect the volatiles at levels required and the ability of the device to discriminate the volatiles in real-world samples. Miniaturized and portable Gas chromatography mass spectrometry equipment is now available and has been tested for a range of applications including water quality testing (Wirth et al., 2012) and the detection of trace materials in forensic applications (Visotin & Lennard, 2016). These could be evaluated for their performance as biosecurity threat detectors. Portable technologies such as electronic noses have been trialled for insect detection in agricultural products with limited success (Wu et al., 2013). Various electronic noses or array-based sensor technologies have been developed for non-invasive diagnosis of disease (reviewed in Adiguzel & Kulah, 2015; Queralto et al., 2014; *Table SM.5.2)*, and these might also be trailed for invasive alien species targets. These technologies are designed to be analogous to biological olfactory systems, where an array of sensors sample an odorant space and pattern-recognition processes identify and classify the odours. Many different types of sensors have been developed for this purpose, including quartz crystal microbalance sensors, metal-oxide sensors, conducting polymer sensors, colorimetric sensors and fluorescence sensors (Adiguzel & Kulah, 2015; Queralto et al., 2014). These differ in their sensitivity, selectivity, response time and their limitations, which are tightly associated with the nature of the sensing mechanism. The limits of detection of the different sensing technologies range from parts per million (ppm) to parts per billion (ppb) (Adiguzel & Kulah, 2015). Each of these limitations needs to be considered when choosing a technology for a given use case.

Table SM.5.2. Advantages and disadvantages of mass spectrometry techniques and selected array-based sensors

Source: Queralto et al. (2014)

Technology	Advantages	Disadvantages
Mass spectrometry-based techniques	Ability to detect cancer-specific Volatile organic compounds; highly standardized techniques; compatible with pre-concentration technique, such as solid phase micro extraction (SPME) and needle trap micro extraction methods to further improve the sensitivity	Expensive; require a skilled operator; long analysis time
Array-based sensors	Cheap, portable, fast, and potential to detect Volatile organic compounds at low concentrations	Cannot identify cancer-specific Volatile organic compounds. Sensor training and standardization are required. Breath Volatile organic compound fingerprints depend on sensor type.
1. Quartz crystal microbalance (QCM)	High precision and sensitivity, diverse range of sensor coatings available	Poor signal-to-noise ratio, sensitivity to humidity and temperature, complex circuitry
2. Au/Pt nanoparticles	Fast response to a diverse set of analytes	Sensitive to humidity
3. Carbon nanotube (CNT)-based sensor	Fast response time, reversible	Sensitive to humidity, less response to saturated hydrocarbons
4. Conducting polymer	Sensitive to various Volatile organic compounds; fast response time	Sensitive to humidity and temperature, poor sensor life Composite
5. Colorimetric sensor	High sensitivity and selectivity high dimensionality; limited humidity effect	Sensor is non-reversible (disposable); for array hydrocarbons, pre-oxidation is required for high sensitivity

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Supplementary material 5.4. Future technologies

Supplement to **section 5.4.2.3**

Table SM.5.3. Summary of surveillance and diagnostic technologies for invasive alien species management

Biosensors and nanotechnology sensors	Combine a biological component with a physicochemical detector ("bioreceptor") to identify chemical substances and thus aid in monitoring many aspects of plant, animal and human health. Biosensors could play a significant future role in the prevention, detection and management of emergency animal disease outbreaks (Neethirajan et al., 2017), with likely comparative benefits for outbreaks of invasive alien species. Nanomaterials can improve the mechanical, electrochemical, optical and magnetic properties of biosensors, leading toward single-molecule biosensors within high-throughput biosensor arrays, one of the challenges of this technology (Mehrotra, 2016). Other challenges include the development of means by which to enhance the signal-to-noise ratio, and ways to enhance transduction and amplification of the signal. These technologies are in their infancy for invasive alien species applications, so it is hard to understand future constraints. They may be related to policy and regulatory issues and animal ethics issues.
CRISPR diagnostics	Microbial CRISPR and CRISPR-associated (CRISPR-Cas) adaptive immune systems contain programmable endonucleases that can be leveraged for CRISPR-based diagnostics. CRISPR diagnostics is likely to be quickly adopted for the rapid and accurate identification of infectious diseases of plants and animals. Gootenberg et al. (2017) found that specific high-sensitivity enzymatic reporter unlocking (SHERLOCK), an in vitro nucleic acid detection platform, was also able to detect Zika virus in clinical isolates (serum, urine or saliva). Further laboratory and clinical work are required to evaluate the performance of CRISPR-based diagnostics in a range of settings – including multiplex point-of-care, which may prove to be its most powerful application.
Multiplexed diagnostic real-time handheld tools	Multiplexed point-of-care testing describes the simultaneous on-site detection of different analytes from a single specimen (Dincer et al., 2017). This approach has recently gained increasing importance for clinical diagnostics, with emerging applications in resource-limited settings such as found in remote locations. Plant and animal disease diagnostics can be undertaken in real time in field settings including a capacity to test for a range of diseases at the same time. Ideally, the system should be able to analyse different types of compounds simultaneously – for example, RNAs, metabolites, proteins, exosomes and cells – and should provide accurate results in all cases. Handheld portal devices have now come in the market that can be used for aspects of this approach (e.g., MinION for portable real-time device for DNA and RNA sequencing).

Disease mRNA biomarkers	A biomarker is a signal released as a component of an organism's response to a particular pathogenic agent or pathogenic process, and thus indicative of the presence of that pathogen or process. Complex biomarkers have now been identified for the sensitive detection of diseases or processes at a stage when they may otherwise have been difficult to identify. Biomarkers are naturally linked to biosensors. Biosensors use a bioreceptor to identify the biomarker, and a transducer to transmit the signal to a receiver that can then interpret and display the outcome. Biosensors based on biomarkers could be deployed alone, or in complex sensor networks. They could also be deployed on unmanned ground-based, aerial or underwater vehicles. Examples by Cowled et al. (2017) and Barkema et al. (2018) show application in animal diseases. Potentially, the approach could also be applied to the rapid detection of some key plant diseases, as miRNA responses are known to occur for viral infections (Zhou & Luo, 2013), bacterial infections (Fahlgren et al., 2007), fungal infection (Campo et al., 2013) and nematode parasitism (Li et al., 2012). Collectively, these advancements are likely to mean that biomarkers become increasingly prominent as tools for invasive alien species applications.

Acronyms

CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
DNA	Deoxyribonucleic Acid
RNA	Ribonucleic Acid

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Supplementary material 5.5. Pathway management – prevention options

Supplement to **section 5.4.3.1**

To eliminate hull biofouling and niche areas fouling, different tools and technologies have been developed in line with following the International Maritime Organization Guidelines on biofouling (The Marine Environment Protection Committee, 2011). Vessel in-water cleaning or treatment is recognized as an important and practical tool to maintain a vessel free of biofouling. Hull grooming (Tribou & Swain, 2015) involves a variety of tools and techniques as manual (soft brushes, scrapers and pads) or mechanical (water jets, rotating brushes with divers or remotely operated vehicles (ROV)). Usually, these techniques do not capture the chemical contaminants associated with the cleaning as well as the organisms (adults, larvae or viable propagules, (Scianni & Georgiades, 2019). Other more complex system includes in-water cleaning tools where the organisms removed are captured and treated (with filtration, heat, biocides, or UV light). Technology is developing fast and in a recent work, Tamburri et al. (Tamburri et al., 2020) evaluated in-water cleaning and capture systems in vessels with different environmental conditions and biofouling levels obtaining good results, according to environmental standards for water quality and biofouling level (*section 5.5*). Depending on the type of biofouling, vessel, available logistic at the place are the tools and technologies that can be effectively applied to reduce the amount of organisms attached (Castro et al., 2020). Soft brushes, water jets or other similar tools are only effective when there is a slime layer, when the macrofouling is well developed, more aggressive tools and techniques are needed. Other more complex methods include the encapsulation or enclosure of the entire structure, usually affordable for recreational vessels and floating docks. If the encapsulation is made only with water, organisms are killed because of the level of anoxia (Keanly & Robinson, 2020), but this method can be accompanied by the use of biocides such as chlorine and acetic acid (Morrisey & Woods, 2015; Roche et al., 2015). Niche areas, such as dry-docking support strips, bow thrusters, rudders, propeller shafts, anodes, and internal pipework, concentrates the highest quantity of biofouling organisms and are usually difficult to clean and maintain. Specially the access and inspection to the internal pipework of recreational vessels is difficult, and the exposure to heat (i.e., thermal stress) is viewed as the most acceptable treatment because it affects biofouling organisms quickly and without environmental contamination (Growcott et al., 2017). For example, for small vessels, Cahill et al. (2019) designed and tested a portable seawater heating for dockside use (with a recirculation system).

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Supplementary material 5.6. Species-led management technologies

Supplement to **section 5.4.3.2**

Fertility control for invasive alien vertebrates - Fertility control technology can be most effectively applied in limiting the growth of low density/small populations for which conventional control methods are impractical, or to slow the recovery of a population following conventional control. Such approaches can also reduce disease transmission (Ramsey, 2007). One labour intensive approach to fertility control is trap-neuter-release programme. This approach requires capture of all or most animals and at this point euthanasia would be a cheaper option, but in cases of strong public opposition trap-neuter-release programme is a more feasible option (Scapin et al., 2019). Depending on the extent to which social structure controls breeding, perverse outcomes may occur (Caughley et al., 1992). For ungulates, more than 50 per cent of fertile females will need to be maintained infertile to achieve a meaningful reduction in the population size, even when fertility rates are low (Hobbs et al., 2000), but fertility reduction rates may be slow (Raiho et al., 2015). Understanding the population demographics alongside modelling of the individual and population-level responses to any chemical or vaccine fertility control approach is important for future management (Cowan et al., 2020) as compensatory demographic processes can reduce fertility control effectiveness. Simulated field trials of female sterilization of European rabbits suggest that high levels of sterility (80 per cent) are needed to achieve population suppression with compensatory survival of sterilized females and recruits (Twigg et al., 2000). Brushtail possum populations subject to female sterility experienced higher immigration rates of dispersing juveniles, mitigating the impact of sterility, demonstrating the need for large scale application of the method (Ramsey, 2005).

The principles of hormonal and immune contraception have been researched for decades. Synthetic hormone implants have been tested and shown to temporarily reduce fertility in species such as macropods and brushtail possums (Massei & Cowan, 2014; Wilson & Coulson, 2016). Gonadotropin releasing hormone has been a key target for wildlife fertility control, using agonists or antagonists of the hormone to disrupt fertility (Herbert & Trigg, 2005). Most fertility control approaches for wildlife have been investigating the concept of immuno-contraception, a process where an immune response to key reproductive proteins or hormones is elicited in the animal and subsequently interferes with reproductive processes. A suite of targets has been investigated for immune contraception approaches, the two most common ones include the zona pellucida protein and the Gonadotropin releasing hormone. Gonadotropin releasing hormone conjugated to an immune adjuvant is available as a commercial contraception vaccine (GonaCon), inducing an immune response in the animal that interferes with the downstream release of hormones affecting ovulation and sperm production (Massei & Cowan, 2014). Gonadotropin Releasing *Hormone (GnRH;* GonaCon™ - 0.032% GnRH) is registered in the United States to control feral horses, donkeys and deer. The zona pellucida protein is formed by a group of glycoproteins that surround the egg cell and play a key role in sperm recognition and binding.

A long-term Australian research programme (1991-2005) also investigated the possibility to deliver subunit zona pellucida protein via genetically modified virus vectors into target species in a self-disseminating vaccine, in a process termed virally vectored immune-contraception (Hardy et al., 2006; McLeod et al., 2008). Preparations made from pig ovaries (available in large quantities from abattoirs) have been shown to be effective in several ungulates, monkeys, seals, bears and marsupials, but not rodents, cats, dogs or wild pigs (Massei & Cowan, 2014). Proof-of-concept that a virally delivered zona pellucida protein3 subunit resulted in long-term infertility was shown in house mice and rabbits (Redwood et al., 2008; van Leeuwen & Kerr, 2008), but has so far not been successful in foxes or cats

(Munks, 2012; Strive et al., 2007). The research programme was disbanded in 2005, due to a combination of perceived public perception risks surrounding the use of genetically modified viruses in wildlife, and a lack of demonstrated transmissibility for the most advanced of the model systems.

A critical component determining the applicability of fertility control is the availability of a suitable delivery mechanism. If problems associated with remote one-off delivery and/or the development of methods for self-dissemination can be overcome, then landscape scale control applications and a broader range of target species may be feasible. Effective means of oral delivery of fertility control agents, or even self-disseminating agents have been extensively researched but are not yet available. Other approaches include the use of the chemical 4-Vinylcyclohexene diepoxide, which acts by depleting the pool of primary follicles in rats, resulting in long term fertility (Dyer et al., 2013). Current research is investigating a palatable formula that will allow effective oral delivery. Chemical products or injectable vaccines will generally be required to have regulatory assessment and approval. A philanthropically funded organization termed Alliance for the Contraception of Cats and Dogs supports research aiming at the development of one-shot non-surgical treatment for these two target species.[4]

Sterile insect technique and other relevant invasive alien invertebrate augmentative approaches - Genetic modification has been available to sterile insect technique for at least 18 years (Alphey, 2002) and produced working products even if these have failed to pass regulatory hurdles. Genetic sexing techniques (or female lethal constructs) are difficult and expensive to develop, but are currently available for use in some control programmes (for example, medfly; Alphey, 2002). The regulatory processes and public concerns however have impeded field trials and releases. Oxitec, the private company developing technologies in this field, found this when it tried to release OX513A *Aedes aegypti* (yellow fever mosquito) in Florida Keys in 2012 (Center for Veterinary Medicine et al., 2016). Improved genetic approaches are under development using RNA interference (Pomcio et al. in review) and clustered regularly interspaced short palindromic repeats (CRISPR)/Cas gene-editing technology to produce non-genetically modified male sterile or female lethal genetic lines (Choo et al., 2018) could also open Sterile insect technique to many more invertebrate pest types and change the economics, practice and success. Current approaches are focussing on gene silencing where possible as regulatory approvals can be easier.

Automation and artificial intelligence are also being used to overcome shortcomings of traditional Sterile insect technique. Computers are better than humans at picture classification tasks (Wu et al., 2015) so this has been applied to solve sex sorting for Sterile insect technique. Verily's Debug project has made its visual sex sorting of adult *Aedes aegypti* (yellow fever mosquito) part of an automated rearing process that has been used with *Wolbachia*-infected *Aedes aegypti* to provide the sterility aspect (Crawford et al., 2020). BigSis[5] has developed a proprietary end-to-end automated insect rearing process that incorporates computer vision for sex sorting and a proprietary method for protecting insects from the deleterious effects of sterilization with ionizing radiation. This has led to products that have successfully avoided or minimized regulatory hurdles by creating a process that works with native wild type strains. For example, BigSis Sterile insect technique products have been cleared by regulators in England in less than a year without permit.

Viral biological control of invasive alien vertebrates - Viral biological control agents are highly taxon-specific to the target species, and risk assessment are needed to assess as far as possible any likelihood of future adaptation to any closely related species, following release. To a large extent, the stability of a

[4] http://www.acc-d.org/

[5] www.bigsis.tech

virus in respect of its target is a characteristic of the viral family to which it belongs. Some viruses (for example, influenza virus) are known to switch species while others (for example, herpes viruses) are generally considered to be highly species-specific.

Viral biological control is ideally suited to the landscape-scale control for terrestrial vertebrate pests and whole-of-river control of invasive freshwater aquatic species. Viral biological control may provide for the long-term sustainable suppression of pest populations and impacts in each of these situations. If part of an integrated pest management strategy (and likely a dominant part), modelling has indicated that Viral biological control can contribute to the eradication of a pest species. In this context, Viral biological control may be particularly effective when combined with fertility control or genetic-control methods.

In Australia, cyprinid herpesvirus 3 (Cy-HV3, carp virus) has undergone extensive efficacy and host-specificity testing and is considered (on the basis of these criteria) to be a suitable viral biological control agent for European carp from this perspective (McColl et al., 2014, 2017). An assessment of the feasibility of using the carp virus as a biological control agent for carp in Australia is underway including extensive published research on public acceptability, risk assessment (including indirect effects – such as its impact on food webs and complex native predator/prey relationships) and disease epidemiology modelling in a natural landscape context (FRDC, 2021). Similarly, a highly-virulent tilapia lake virus (TiLV) against invasive tilapia fish has recently been described which may also be highly specific (Bacharach et al., 2016). The potential use of this virus as a biological control tool in Australia is currently at the scoping stage. The time required to identify, evaluate and obtain approvals for a potential viral biological control agent, including strong public and political support is generally in the order of five to 15 years. As for classical biological control, efficiencies may be gained from the adoption of an agent that has been deployed successfully in another country. The evaluation of potential viral biological control agents generally requires the use of a biological containment level 3/4 facility.

Ribonucleic Acid interference (RNAi) is a generic approach to altering gene expression, using highly specific gene-silencing constructs the efficacy and versatility of which has been demonstrated across a wide range of plants, invertebrates and vertebrates. Although some generic principles will apply, most applications will be specific to particular hosts (whether plants, invertebrates or vertebrates) and to the cells within these hosts that the RNAi is seeking to target. RNAi, where effective, has potentially very broad applications against highly specific species and upregulated gene targets. RNAi constructs need to be designed to eliminate any effects on potential non-target species. One of the key advantages of RNAi is that cellular changes are not inherited across a generation, so host is not itself genetically modified. The challenge is delivery of the RNAi molecules to the relevant target cells in a broad population. Delivery to the mucosal epithelial cells of chickens, for example, is very different to delivery to gonads of prawns or to wild flying insects. Where this difficulty can be overcome, the approach has enormous potential to the agricultural, horticultural and livestock industries, as well as to conservation management and public health. RNAi also provides a highly specific means by which to augment the resistance of plants, animals and people to key diseases. RNAi could reduce the use of conventional chemicals, and has the potential to be used to assist in production of sterile flies within a sterile insect technique programme (*section 5.4.3.2*). RNAi may also have application for altering the expression of highly- conserved genes across related species, although this is yet to be explored. The lead time for the development of a new product would depend largely on whether an effective delivery mechanism has been identified. If it has, then five to 10 years might be required to bring the application from basic research through to a registerable product. If a delivery system has not been identified, then the lead time will be very difficult to estimate. Once one RNAi application domain has been registered, then the process is likely to be simpler and faster for future applications.

Genetic control approaches – Genetic-control approaches have either not moved beyond the proof-of-concept stage (for example, viral vectored immunocontraception and daughterless carp), or remain at a development phase. Early work conducted in Australia showed that sex biasing in fish populations was possible (Thresher et al., 2014). Naturally occurring Trojan y-chromosome system has been worked on extensively in the United States of America (Wang et al., 2014), although no practical control attempts have been made despite being a non-genetically modified based approach. The T-Sry mouse system is also at the developmental stage in the United States, resourced and supported through an international Genetic Biocontrol of Invasive Rodents consortium. Other naturally occurring sex biasing genetic mechanisms occur in many different types of organisms (Wedell et al., 2019). All of these approaches have developed a vast body of knowledge about fertility targets and the reproductive biology of the target species, upon which modern gene-technology approaches can be built. Work on synthetic gene-drive system has only been possible in the last ten years with the discovery of CRISPR (and some related precision technologies such as transcription activator-like effector nuclease) which allow gene deletions or precise editing of a few nucleotides in single genes (Cong et al., 2013; Mali et al., 2013). The most commonly recognized synthetic approach is the "homing gene-drive" system, but it is only one synthetic approach and has only been successfully developed in mosquitos and not yet in vertebrates as the approach is not easily translatable. A working homing gene-drives can theoretically force deleterious gene constructs (for example, sex biasing gene) into a wild population following the release of only a few modified individuals (Esvelt et al., 2014). The gene-drive cassette includes the CRISPR/Cas9 gene scissors which guide RNA to the point of incision in the genome and the deleterious gene "payload" to be inserted. The CRISPR/Cas9 cassette can copy itself between precise identical locations on maternal and paternal chromosomes. Following a successful sexual reproductive event with either a mother or father carrier, all offspring will carry the gene-drive on both copies of the targeted chromosome. All of their descendants will also carry and pass on the gene-drive to all offspring. In theory, therefore, a single individual released carrying a gene-drive cassette can eventually transfer the cassette to all individuals in a descendent population after a series of generations. All synthetic approaches require genetic modification of the target organism and allows broadening of the types of deleterious genes that could be included as part of the gene-drive cassette beyond sex-biasing mechanisms. These could include increased individual susceptibility to an otherwise benign pathogen or chemical applied as an additional control measure, or other changes to other desired species-specific genetic targets. The details of the approaches becoming available are changing fast (for example, Dhole et al., 2018; Prowse et al., 2017), so it will be important to stay up to date regarding developments for genetic mechanisms for suppressing established invasive alien species globally (e.g., Legros et al., 2021). The initial research and development and implementation costs for genetic control are likely to be high and, for non-gene-drive based systems, are likely to continue until long-term control has been achieved (or not).

In almost all cases synthetically modified target organisms with invasive alien species control in mind will be classed as genetically modified organisms and will be subject to genetically modified regulatory approval. Many international forums therefore bring together scientists (genetic, technical and risk analysis), ethicists and regulators to discuss how gene-drive research could and should be conducted. Large sectors of the public are very concerned about the use of genetically modified technologies for pest, weed and disease control, particularly in a commercial context. Perceived versus scientifically assessed levels of risk, cultural values, the degree to which the situation has wide public support and the degree to which permission for the use of this technology remains in the public control are all relevant issues for public acceptability in the short and long-term. A substantial body work is appearing addressing this (Delborne et al., 2018; George et al., 2019; Jones et al., 2019; Kokotovich et al., 2020). The challenges of understanding pubic acceptability of genetic control approaches have been exemplified by the case of introducing the genetically modified *Castanea dentata* (American chestnut) to counter devastating *Cryphonectria parasitica* (blight of chestnut; Barnhill-Dilling et al., 2019) and the cases for release of genetically modified mosquitos to protect the communities in Africa and the Americas from malaria (Cisnetto & Barlow, 2020) and Zika virus (Adalja et al., 2016) respectively (Resnik, 2018, 2019). The cases, and their successful use will probably define further applications of these technologies globally. It is likely that public acceptability will vary from case-to-case. For example, the acceptability of a genetic-control approach for mice may differ when applied either: (a) to mitigate a threat to the biodiversity on an island; or (b) to mitigate a threat to grain production and storage (Carter et al., 2022). It will be important to place the communication of risks in the context of alternative methods. Importantly, the technology has been accepted as a research and development focus by some but not all conservation non-governmental organizations.

The regulatory framework for this technology exists in some countries, and the processes and permits required are generally understood. In the instance where genetic control is based on standard genetic modification technology, this would parallel processes for the registration and release of genetically modified crops. Where a genetic technology involves simple gene-editing and no additional Deoxyribonucleic Acid (DNA) from other species, there are lower levels of regulation in some parts of the world (e.g., Japan, Australia and United States). There is concerted international debate to ensure that gene-drive research, development and deployment are conducted with appropriate social, ethical and legal oversight. Use of CRISPR/Cas 9 is also subject to patents and the patent holders are being very cautious about use in most contexts. There is freedom-to-operate in terms of the basic research, but the development phase will require licences for commercial or general deployment.

Acronyms

CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
DNA	Deoxyribonucleic Acid
GnRH	Gonadotropin Releasing Hormone
RNA	Ribonucleic Acid
RNAi	Ribonucleic Acid Interference

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Supplementary material 5.7. Ecosystem restoration

Supplement to **section 5.4.3.3b**

Ecosystem Restoration: Indigenous peoples may not use more western terms of "management" and "restoration" when working to change the impacts of invasive alien species in their country, landscapes and culturally and spiritually important places. Where Indigenous Peoples care for their traditional lands impacted by invasive alien species, they do not use scientific terminologies. Examples include a) traditional fire management practices used to manage invasive alien plants by the Yellomundee Aboriginal Bushcare employing Yellomundee Firesticks in New South Wales, Australia and b) traditional approaches to reducing the impacts of invasive alien invertebrates in tea-plantations surrounded by sacred groves, social forestry, gardens, parks and small rivers in North Bengal. The Bunuba Aboriginal rangers of the Fitzroy River in Western Australia look after country in accordance with their culture and customs, using a place-based approach across the broader landscape by identifying the values of those places and then managing the vegetation at those sites by developing specific invasive alien plant management plans based on site cultural significance to ensure a holistic approach to maintaining a healthy country. This highly successful place-based approach is a type of site or ecosystem-based approach in partnership with the Western Australian Government Department of Biodiversity Conservation and Attractions (DBCA) and Monash University (Ens et al., 2015).

Research through the Kimberley Land Council considered the governance context of weed management by Aboriginal ranger groups in the Kimberley, northwest Australia. The Kimberley is the traditional homelands of diverse Aboriginal peoples from about 27 different language groups. The research focuses on the changing context of native title which has led to about 93.5 per cent of the Kimberley being recognized, with the majority of the weeds work undertaken by indigenous ranger groups from the community. Bardi Jawi Ranger Kevin George emphasized the role of traditional authority in weeds management. Traditional authority is an important part of the way decisions are made between Aboriginal people, their organizations, and their "law bosses" or elders. For Kevin, weed management projects by governments or non-government organizations need to respect traditional authority, as well as local knowledge and priorities. Weed management is not just a technical, scientific, economic or ecological issue. Weed management is about how relationships between people, their lands and waters – their country – are respected (Ens et al., 2015; **Box SM.5.1**).

Box SM.5.1. Wunambal Gaambera Healthy Country Planning, Kimberley Northwestern Australia.

The Wunambal Gaambera Aboriginal people have native title over Wunambal Gaambera Country, which covers about 2.5 million hectares of land and wundaagu (sea), in the north Kimberley region of northern Australia (Wunambal Gaambera Aboriginal Corporation, 2010). This Country has been home to the Wunambal and Gaambera people for thousands of years. The Wunambal Gaambera people, as their ancestors did, call this land "our Uunguu" (our living home). In the Lalai, the Law for caring for our country was made. The ancestors passed their stories down from generation to generation from Wanjina who left their images and stories in rock art throughout Wunambal Gaambera Country.

The Wunambal Gaambera people developed a Healthy Country Plan to collectively determine the Targets and Threats to the Country. Their Healthy Country Plan grew from work that the Wunambal Gaambera traditional owners, have been doing since the late 1990s. These combined activities have helped the Wunambal Gaambera people tell others about the importance of looking after the country and to make sure their unique cultural and natural assets and values are kept healthy and passed to future generations. "Everything in our Uunguu is connected". Through planning workshops ten key nested important Targets were identified by the Wunambal Gaambera people. The Wunambal Gaambera people collectively identified threats for each target with all targets being interconnected. The Health of each Target was identified by including land and seascape health, cultural health and biophysical health, adding to an overall health rating for each target. Each threat was ranked between low to very high based on what people knew when the plan was written. The Wunambal Gaambera people determined that they had to make sure that all sides of the threats are looked at and managed properly. One threat was called weeds and another threat was called feral animals.

The weeds and feral animal threats had an overall threat rating of High which means the threat may cause serious damage to all or part of the targets which it impacts if the current situation or rate of damage continues. If this happens it would be very expensive and difficult to make the target healthy. Some of the problems caused by weeds to the Country include clogging up the homes and places (habitats) of plants and animals "that should be in our country", making plant and animals "that should be here" sick and, in some cases die and disappear, impeding travel and collection of food and medicine plants, hunting and fishing and making it hard for animals to move through country, causing pollution and messing up yawal (waterholes).

Some of the threats identified from feral animals were: damaging wulo (rainforest) polluting and muddying yawal (waterholes) with droppings and carcasses, spreading weeds and bringing disease that can harm plants, fish and seafoods such as our marlinju (oysters), and parasites that can cause animals like aamba (kangaroos and wallabies) to get sick, damaging rock art by rubbing against the paintings, trampling some of our food and medicine plants. The introduced cane toads impact on animals like the wijingarri (northern quoll) which are special in dreaming stories, compete with and eat small meat foods like diigu (birds), poison and kill small meat food like wobarda (water monitor) and wijingarri (northern quoll) and also disturb cultural sites.

Having established their Vision, 10 targets and threats the Wunambal Gaambera people established objectives they would like to achieve to keep the targets healthy and fix or lessen the threats. The objective relevant to invasive species was that: by 2015 we will be managing and controlling pest species on Wunambal Gaambera Country and by 2020 pest species will have a smaller impact.

The Wunambal Gaambera approach is neither referred to as management or restoration, but rather as reducing threats to key targets a critically important strategic approach to identifying the problem, impacts and then tackling the impacts of, in this case pests, weeds and feral animals and interconnections. There is often a difference in perceptions between indigenous and non- Indigenous Peoples around feral animals, by which the western scientific approach will work to eradicate a species from the country, whereas the Wunambal Gaambera will see these feral animals as having been born on country and so having connections to the land they were born on, in the same way as the people do. Wunambal Gaambera have concerns around ethics of wasting food and cannot bear to see an animal shot or culled and left to rot on country. Ownership of these animals reverts to the owner of the land on which the animal was born, with these people being the decision makers about the future of the animal, and the meat for example which may come from an animal. It is complex and needs to be factored into any decisions about how feral animals are to be treated (Wunambal Gaambera Aboriginal Corporation, 2010)

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Supplementary material 5.8. International Standards for Phytosanitary Measures

Supplement to **section 5.3.1.2**

The International Plant Protection Convention (IPPC) International Standards for Phytosanitary Measures (ISPMs) greatly assist in management strategies by providing global standards in plant health management.[6] ISPMs cover a wide range of topics, including: pest risk analysis, surveillance, phytosanitary pest status, pest reporting, regulated pest lists, pest eradication, export certification, import control, inspection and emergency measures. There are also a number of ISPMs that are specific to the international movement of regulated articles, such as: biological control agents, wood packaging material, wood, seeds, growing media in association with plants, processed products, and used vehicles, machinery and equipment. These ISPMs are relevant to Article 8(h) since the regulated articles are potential pathways for the introduction and spread of invasive alien species:

General ISPMs:

- ISPM-1 Phytosanitary principles for the protection of plants and the application of phytosanitary measures in international trade
- ISPM-5 Glossary of phytosanitary terms
    - Supplement 1: Guidelines on the interpretation and application of the concept of "official control" and "not widely distributed" (2012)
    - Supplement 2: Guidelines on the understanding of "potential economic importance" and related terms including reference to environmental considerations (2003)
    - Appendix 1: Terminology of the CBD in relation to the Glossary of phytosanitary terms (2009)
- ISPM-20 Guidelines for a phytosanitary import regulatory system

ISPMs related to pest status and pest risk analysis:

- ISPM-2 Framework for pest risk analysis
- ISPM-8 Determination of pest status in an area
- ISPM-11 Pest risk analysis for quarantine pests
- ISPM-19 Guidelines on lists of regulated pests

ISPMs related to pathways:

- ISPM-3 Guidelines for the export, shipment, import and release of biological control agents and other beneficial organisms
- ISPM-15 Regulation of wood packaging material in international trade
- ISPM-38 International movement of seeds
- ISPM-39 International movement of wood
- ISPM-40 International movement of growing media in association with plants for planting
- ISPM-41 International movement of used vehicles, machinery and equipment

ISPMs related to surveillance, eradication and pest free areas:

[6] https://www.ippc.int/en/core-activities/standards-setting/ispms/

- ISPM-4 Requirements for the establishment of pest free areas
- ISPM-6 Surveillance
- ISPM-9 Guidelines for pest eradication programmes

Acronyms

IPPC	International Plant Protection Convention
ISPM	International Standards for Phytosanitary Measures

Supplementary material 5.9. Examples of effective surveillance strategies

Supplement to **section 5.5.2**

Some examples of specific surveillance include the Mamalu Poepoe programme which is coordinated through the Hawaii Invasive Species Council[7] targeting invasive ants, mosquitoes, coconut rhinoceros beetle and Africanized bees at airports (Kaufman & Atwood, 2019). The main objective of the programme was to provide baseline data on invasive ants at airports. The programme was useful for early detection of other invasive alien species not already present. Swarm traps were used to detect strains of Africanized bees and Biogent sentinel traps for detection of adult mosquitoes. Trials were conducted to identify the most efficient and cost-effective traps and lures that are more sensitive to detection of mosquitoes at airports. There are cooperative agricultural pest surveys[8] which conduct science-based national and state surveys targeted at specific plant pests, diseases, and weeds identified as threats to United States of America's agriculture and environment. These activities are accomplished primarily under the United States Department of Agriculture funding that is provided through cooperative agreements with state departments of agriculture, universities, and other entities. Surveys conducted through the cooperative agricultural pest surveys programme are a second line of defence against the entry of harmful plant pests and weeds, in addition to inspections of commodities at the border. These surveys enable the programme to target high-risk commodities, gather data about pests specific to a commodity, and establish baseline data on pests that were recently introduced into the United States. The objective of the cooperative agricultural pest surveys programme is to provide a survey profile of plant pests in the United States deemed to be of regulatory significance through early detection and surveillance activities.[9]

In Mexico, surveys are carried out to target invasive birds and are designed around areas of likely colonization in urban wooded parks. The repeated surveys build up a registry of invasive bird species of differing habitat and seasonal preferences across cities and provides information on their invasiveness over time (Pineda-López et al., 2013). New Zealand's marine high risk Site Surveillance is a programme of surveys targeted at early detection of invasive alien marine species in the country which reports on range extension of these species already established. The surveys are undertaken biannually at ports and harbours around New Zealand that receive relatively high amount of international shipping and are therefore considered to be most at risk. The methodology consists of risk-based stratification of the marine environment within each harbour, which is then used to prioritize allocation of sample effort based on the likely distribution of founding populations of the target species (Inglis et al., 2006). Since its inception in 2002, the programme has detected one primary target pest species (*Sabella spallanzanii* (Mediterranean fanworm) in 2008), 16 invasive alien species that were not previously known from New Zealand, and has recorded numerous range extensions for invasive alien marine species including *Sabella spallanzanii*; the tunicates, *Styela clava* (Asian tunicate) and *Eudistoma elongatum*; the decapod crustaceans, *Charybdis japonica* (lady crab) and *Metapenaeus bennettae* (bay prawn); *Arcuatula senhousia* (Asian date mussel); and the algae *Undaria pinnatifida* (Asian kelp) and *Grateloupia turuturu* (devil's tongue weed) (Seaward et al., 2015).

The National Plant Health Surveillance System managed by the Australian Government Department of Agriculture, Water & Environment is designed for early detection of Australia's top 40 unwanted and alien "National Priority plant or quarantine pests and diseases" (Australian Government, 2019).

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[7] https://dlnr.hawaii.gov/hisc/

[8] http://caps.ceris.purdue.edu/

[9] https://www.aphis.usda.gov/aphis/ourfocus/planthealth/pest-detection

Surveillance is carried out by State governments, the Australian government and plant industries with the support from the community. Targeted programmes are conducted at international entry points such as sea and airports and also provide data to support trade and market access to Australian producers (Anderson et al., 2017; Plant Health Australia, 2018). The system is supported by a nationally integrated plant biosecurity diagnostic network which focus on building diagnostic capability and capacity across Australia and New Zealand (Plant Health Australia, 2018).

Australia is one of the few countries in the world that is free of varroa mites that impact *Apis mellifera* (European honeybee) hives. This pest of bees has been kept out through a science-based and very targeted and effective surveillance programme using sentinel hives (*section 5.4*) at ports of entry where surveillance efforts are prioritized based on risk maps (*section 5.2*; Heersink et al., 2016)

Australia's National arbovirus monitoring programme monitors the distribution of economically important arboviruses of livestock (*section 5.4*). Data is gathered throughout Australia by serological monitoring of sentinel cattle herds and trapping of insect vectors. The programme design is based around the probability of arbovirus transmission and sites are monitored to ascertain areas of disease freedom and to detect new strains of virus and assess seasonal intensity in endemically infected areas (Animal Health Australia, 2019).

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Supplementary material 5.10. Examples of eradication programmes

Supplement to **section 5.5.3**

According to Island Conservation's Database of Island Invasive Species Eradications (DIISE, 2018), there have been over 1,500 eradication attempts of vertebrate alien species. As a result, 38 mammal species have been eradicated, in almost 1,100 events, with an 88 per cent success rate on 798 islands followed by 9 bird species, in 22 events, with an 82 per cent success rate on 22 islands. There is only one case of successful reptilian eradication, which took place on the Seychelles. In the case of invertebrates, 81 invasive alien species have been eradicated from 50 islands (Glen et al., 2013). Lastly, 75 invasive plant species have been eradicated from 19 islands. However, most biodiversity threatened by invasive alien species on islands occurs on islands too big for current technologies to achieve eradications, which prompted greater focus on new genetic approaches which helps to push these boundaries (Campbell et al., 2019).

One invasive alien species group that has been strongly targeted in eradication programmes are ants, which cause impacts to human wellbeing, the environment and agricultural systems. A global study principally carried out on continents including 316 eradication campaigns targeting 11 species had a success rate of 66 per cent (n=236, 75 per cent). Over 50 per cent of these campaigns remain unpublished (Wylie et al., 2016). These have been done in the Seychelles, United States of America, Galápagos islands, Australia, New Zealand and People's Republic of China. Most of the successful programmes have been done in Australia and New Zealand (Wylie et al., 2016). The cost of implementation increases with the increase in area and is higher compared to costs of mammal eradication. The total area that invasive ants have been eradicated worldwide is approximately 9,500 ha. The largest successful eradication of red imported fire ants to date, is in the greater Brisbane metropolitan area in Australia (over 100 km^2) which has already cost the country over AU$ 400 million. The programme used multiple methods as, aerial broadcast, hand broadcast, and nest drenching, and included the use of novel technologies to monitor new outbreaks. Overall, the most frequent programmes have been on *Anoplolepis gracilipes* (yellow crazy ant) while the most successful ones have been on *Pheidole megacephala* (big-headed ant). The chemical substances: fipronil, hydramethylnon, and juvenile hormone mimics are commonly used, often in combination. The methods used for delivering baits were mainly by hand (56 per cent), aerially by helicopter (36 per cent), multiple methods (5 per cent) and by drenching nests with an aqueous solution (2 per cent). The number of successful eradication programmes against ants has increased significantly in recent years due to effective surveillance which picks up new incursions quickly (McNaught et al., 2019) and effective eradication approaches being developed for allowing rapid response (Hoffmann et al., 2016), however many other ant eradication programmes are still ongoing after many years because they were not targeted early enough (Wylie et al., 2016). It is also necessary to develop better methods of removal, including more natural history and proper taxonomic identification of taxa to increase the efficacy of chemical substances and baits, to minimize or mitigate non-target risks as well as to develop better technologies to confirm eradication (Hoffmann et al., 2016).

In the case of plants, the success rate of eradications programmes is generally low (*Figure 5.23*) because of the soil seedbank and the difficulty to detect and remove them (Panetta & Timmins, 2004). Frequently, the longevity of the seed bank of some species is unknown. For this reason, it is necessary to conduct long-term surveillance to detect emerging seedlings. Eradication campaigns have been most often attempted in the agricultural sector (Pluess et al., 2012). In a review (Rejmanek & Pitcairn, 2002) concluded that infestations over 1000 ha are unlikely to be eradicated. "Knowledge of the extent of a weed incursion (the "delimitation" criterion) is considered fundamental for eradication success, as an incursion will progress from any infestations that remain undetected and thus uncontrolled" (Panetta & Lawes, 2005). Generally, weed eradication programmes require 10 years or more to achieve their objective, because even after the last plant has been removed monitoring is necessary to continue for the life of the seedbank (Panetta, 2007). The optimal time to stop monitoring and end the programme is really an economic trade-off between the cost of continued surveying and the cost of escape and damage if eradication is declared too soon (Regan et al., 2006).

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Supplementary material 5.11. Smallholder farmers and the management of *Spodoptera frugiperda* (fall armyworm)

Supplement to **section 5.5.5**

Asare-Nuamah et al. (2022) and Koffi et al. (2020) found that almost 90 per cent of their sampled farmers from Ghana used synthetic pesticides for fall armyworm control. Tambo et al. (2020) and Houngbo et al. (2020) also reported that 87 per cent and 91 per cent of sampled farmers in Rwanda and Benin, respectively, applied synthetic pesticides to control fall armyworm. The widespread use of synthetic pesticides has been attributed to the distribution of free or subsidized pesticides by several African governments in response to the fall armyworm invasion (Asare-Nuamah, 2022; Day et al., 2017; Tambo, Day, et al., 2020). Unfortunately, some of the farmers use restricted and highly toxic synthetic pesticides, and there is little or no use of personal protective equipment while spraying the pesticides, thereby posing high risks to human health (Kansiime et al., 2019; Murray et al., 2019, 2021; Rwomushana et al., 2018; Tambo, Day, et al., 2020).

Nearly 40 per cent of the papers reported evidence of farmers' control of fall armyworm using biopesticides, which are low-risk products compared to synthetic pesticides. The biopesticides are mostly neem-based products, and extracts of other plants such as tobacco, chilli and *Mucuna pruriens* (velvet bean) (Dassou et al., 2021; FAO, 2018; Kansiime et al., 2019; Kumela et al., 2019; Murray et al., 2019). Rwomushana et al. (2018) found an increase in the use of biopesticides for fall armyworm control in Ghana, due to policy effort by the government to promote their usage. The physical control methods include handpicking of fall armyworm egg masses and caterpillars, as well as the destruction of infested plants. A study by Tambo et al. (2020) has shown evidence that households with few members (who are thus more likely to be labour-constrained) and households who cultivate larger plots, have lower likelihoods of engaging in handpicking of fall armyworm due to its labour intensiveness. There are also concerns that the handpicking of fall armyworm may increase the labour burden of women and children (Harrison et al., 2019; Tambo, Day, et al., 2020; 2019; 2020). It was found that the use of cultural methods for fall armyworm management was popular in areas where extension programmes (plant clinics and information and communications technology-based extension campaigns) have been used to promote integrated pest management (Tambo et al., 2019; Tambo, Kansiime, et al., 2020; Tambo, Uzayisenga, et al., 2020).

An exception is the use of fish soup, which was identified as a traditional method of controlling fall armyworm in Malawi (Murray et al., 2019). Rwomushana et al. (2018) suggested that the use of the traditional methods was becoming popular in Zambia as the number of farmers using them for fall armyworm control doubled between 2017 and 2018. They attributed this to the lack or reduced distribution of pesticides by the Zambian government and the use of traditional non-chemical approaches to maize production by smallholder farmers in the country.

Factors constraining the management of fall armyworm

This fall armyworm information constraint is partly due to limited capacity of extension workers (Kassie et al., 2020; Murray et al., 2019; Tambo et al., 2019), who are key sources of information for many smallholders. Hence, farmers tend to be exposed to incorrect or contradictory information from different sources (Abukari et al., 2021) or do not know what to do to combat the pest (FAO, 2018), or lack an understanding of the risks associated with the indiscriminate use of pesticides against fall armyworm (Murray et al., 2019).

Effectiveness of the management practices

Most of the studies examined the effectiveness of the fall armyworm management practices based on farmers' perceptions. Pesticides were generally perceived to be effective against fall armyworm (FAO, 2018; Houngbo et al., 2020; Rwomushana et al., 2018; Tambo, Kansiime, et al., 2020). For example, Tambo et al. (2020) found that in each of their four study countries (Ghana, Uganda, Zambia and Zimbabwe), more than 90 per cent of the synthetic pesticide users reported that this method was effective against fall armyworm. In Ghana, 88 per cent of smallholder farmers who used biopesticides claimed that it was effective (Tambo, Kansiime, et al., 2020), while in Namibia, almost all commercial farmers who applied pesticides to control fall armyworm said that the method was effective (FAO, 2018). However, according to Kumela et al. (2019) 60 per cent of sampled farmers in Kenya mentioned that pesticides were not effective for the control of fall armyworm. Similarly, Koffi et al. (2020) noted that for nearly two-third of farmers synthetic pesticides were ineffective when sprayed on maize leaves, but 92 per cent of the farmers who received some training and adopted target application of pesticides were satisfied with the effectiveness of the pesticides, pointing to the importance of farmer training in the successful management of the pest.

The perceived degree of effectiveness of other fall armyworm management practices varies considerably across studies. For instance, early planting, handpicking, planting resistant varieties, crop rotation and replanting were largely perceived as extremely or somewhat successful in Namibia (FAO, 2018). Conversely, early planting and handpicking were rated as relatively ineffective against fall armyworm by farmers in Benin (Houngbo et al. 2020). The application of ash was, however, unsuccessful in both Namibia (FAO, 2018) and Benin (Houngbo et al., 2020). According to Rwomushana et al. (2018) majority of farmers in Ghana and Zambia who used physical and cultural methods such as handpicking, weeding and uprooting and burning of infested plants to control fall armyworm reported these non-effective. Similarly, Murray et al. (2021) noted that most of the cultural control methods were c ineffective against fall armyworm in Kenya. As noted by Tambo et al. (2020), farmers' perceived effectiveness of the various fall armyworm management is likely influenced by several factors, including the level of fall armyworm infestation, the timing of application of the practice, and field conditions.

Several of the studies also explored the effectiveness of the fall armyworm management practices using statistical analysis, instead of farmers' perceptions. The results generally showed that farmers who used fall armyworm management practices achieved positive outcomes in terms of reduced yield losses (FAO, 2019), increased maize yield (Bariw et al., 2020; Kassie et al., 2020; Tambo, Uzayisenga, et al., 2020), increased maize consumption (Tambo, Uzayisenga, et al., 2020), and reduced hunger (Tambo et al., 2021). Three of the studies (Bariw et al., 2020; Kassie et al., 2020; Tambo, Day, et al., 2020) further showed that greater gains were achieved when farmers used a combination of the fall armyworm management practices. For example, using survey data from Ghana and Zambia, Tambo et al. (2020) showed that spraying of pesticides alone was associated with maize yield gain of 90 per cent, while handpicking alone did not significantly enhance yield; but combining the two methods produced maize yield gains of 125 per cent. Likewise, Kassie et al. (2020) found that individual fall armyworm control measures were ineffective in preventing yield losses, but combining different control strategies, such as using chemicals and handpicking or handpicking and ash, was effective in mitigating yield loss due to fall armyworm in southern Ethiopia.

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Supplementary material 5.12. Case study: classical biological control of *Oryctolagus cuniculus* (rabbits)

Supplement to **section 5.5.5.3**

Box SM.5.2. *Oryctolagus cuniculus* (rabbits) biological control in Australia

Myxomatosis is caused by a poxvirus (family *Poxviridae*, genus *Leporipoxvirus*) and is vectored by insects. In rabbits of the genus *Sylvilagus* (cottontail rabbits) in the Americas, infection causes only localized skin tumours, but resulted in high mortality in European rabbits. The virus was released in Australia in the late 1940s which initially reduced the number of rabbits to the tune of 90-99 per cent (*Figure SM.5.1*). However, the individuals that survived developed immunity and reduced the impact of myxomatosis. In 1968 and 1993, *Spilopsyllus cuniculi* (European rabbit flea) and *Xenopsylla cunicularis* (Spanish rabbit flea) were released to enhance transmission in hot dry regions (Cooke, 2014).

In the mid-1980s, a novel disease of rabbits emerged, rabbit haemorrhagic disease, caused by a single-stranded positive-sense Ribonucleic Acid (RNA) virus (RHDV1). In 1991, RHDV1 was imported into containment in Australia for assessment and testing. Despite strict biosecurity and quarantine, within months the virus had escaped to the mainland and spread rapidly. Both the escape and the subsequent rapid spread were most likely vectored by flying insects. In 1996, RHDV1 was officially registered in Australia as a pest control agent (Cooke, 2014; Saunders et al., 2010). A vaccine for the released strain was subsequently developed and made available to the domestic and pet rabbit trade (AVA, 2011).

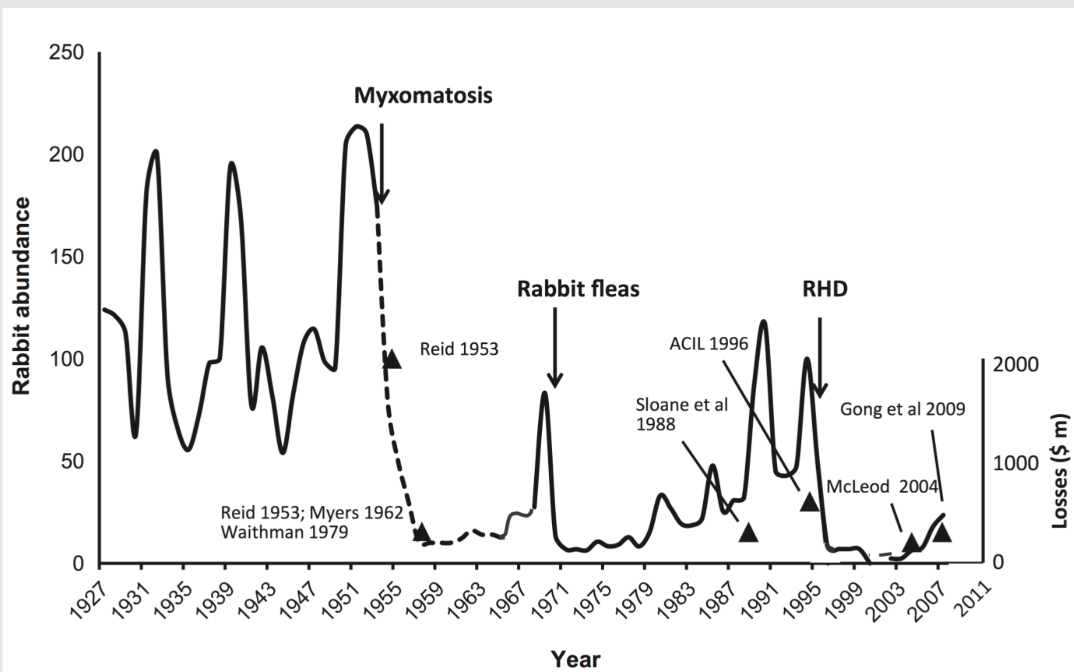

Figure SM.5.1. Diagram showing how *Oryctolagus cuniculus* (rabbits) abundance in semi-arid South Australia has varied through time in response to the release of biocontrol agents. The estimated

Australia-wide economic losses to rabbits (triangles) are also shown. Scale for losses shown on right-hand side of figure. Adapted from Saunders et al. (2010)

The original release of RHDV1 in Australia was estimated to have cost about AU$ 12 million over seven years for research, including safety aspects. The return on that investment has been estimated at AU$ 350 million annually (Saunders et al., 2010). Considering myxomatosis and RHD together, the overall value to the wool and meat industry in Australia is estimated to have cumulative economic benefits of about AU$ 70 billion in 2011 (Cooke et al., 2013). Regardless, post-RHD rabbit populations still cost the Australian wool and beef industry an estimated AU$ 200 million annually (Gong et al., 2009). Sustained RHD biological control has resulted in the recovery of three previously threatened desert mammal species such that they now qualify for a downgrading of their categorization on the International Union for Conservation of Nature (IUCN) red list (Pedler et al., 2016). In arid zones, sustained low rabbit populations has led to the significant regeneration of native vegetation (Sandell, 2002).

Acronyms

AU$	Australian dollar
RHDV	Rabbit Haemorrhagic Disease Virus
RNA	Ribonucleic Acid

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Supplementary material 5.13. Case studies – role of national and international networks and regional partnerships in management

Supplement to **section 5.6.3.1**

Local - In Hawai'i, island-based partnerships (referred to as invasive species committees, or ISCs) have operated on all six of the main, non-privately held Hawaiian Islands since 2001 (Kraus & Duffy, 2010). The invasive species committee (ISC) structure consists of an independent committee of interested parties (e.g., Federal and State agencies, private organizations, landowners, or business association) who are supposed to jointly identify and eradicate the most-threatening invasive alien species. The actual control work is led by an ISC manager, a field leader and field crew, supported by information officers, data management and sometimes also including a volunteer work force. While sustained funding sources remain as issue, the model has been successful in circumventing political interference and gaining public support (Kraus & Duffy, 2010).

National - Countries which hold overseas territories provide an example of subnational collaboration. In 2005, the International Union for Conservation of Nature (IUCN) French Committee launched an initiative on invasive alien species in the French overseas territories with the aim of improving access to information, increasing management capacity, and strengthening cooperation among the thirteen overseas territories and with their neighbouring countries (Soubeyran et al., 2015). With a budget of 140,000 € per year, two action plans were implemented between 2005 and 2011, by informal working groups consisting of a network of national and local experts and stakeholders from research institutions, non-governmental organizations and public agencies (*section 5.6.3.1*). Outcomes of the initiatives include a website[10] with a species database (630 alien taxa), a bibliographic database (490 references) and numerous documents such as protocols for control, guidelines for preventive action and regulations in force, and regional workshops to promote transnational cooperation (Soubeyran et al., 2015).

Global - **Section 5.4.1** and **Table 5.4** listed databases relevant for planning and implementation of management. In addition, some examples are provided here of international networks assisting management of invasive species at global scale namely Invasive Species Specialist Group (ISSG), The Inter-American Biodiversity Information Network (IABIN), Asia-Pacific Forest Invasive Species Network (APFISN), European Network on Invasive Alien Species (NOBANIS), Centre for Agriculture and Bioscience International (CABI) and the European Alien Species Information Network (EASIN).

Networks: The ISSG is a global network of scientific and policy experts on invasive species, organized under the auspices of the Species Survival Commission (SSC) of the IUCN. The Invasive Species Specialist Group (ISSG) was established in 1994. It currently has 196 core members from over 40 countries and a wide informal global network of over 2000 conservation practitioners and experts who contribute to its work. The ISSG promotes and facilitates the exchange of invasive species information and knowledge across the globe and ensures the linkage between knowledge, practice and policy so that decision-making is informed (Pagad et al., 2015). The two core activity areas of the ISSG are policy and technical advice, and information exchange through our online resources and tools and through networking. The ISSG used to publish a biannual newsletter "Aliens" featuring articles on

[10] www.especes-envahissantes-outremer.fr

issues related to invasive species. The ISSG manages the Global Invasive Species Database (GISD) which is an online, freely available premier resource of information on invasive species, their ecology, spread, management, and impacts. The GISD aims to increase public awareness about invasive species and to facilitate effective prevention and management activities by disseminating specialist's knowledge and experience globally to a broad audience. The IUCN and its ISSG have also recently published a global standard for the Environmental Impact Classification for Alien Taxa (EICAT; IUCN, 2020b).

IABIN for invasive species was established in 2002 as the first thematic network (I3N) (Grosse et al., 2006), formed through an agreement between countries in the Americas. The objective of I3N was to facilitate cooperation on invasive alien species information discovery, collection, management, and distribution, and provide training on the use of tools developed and freely distributed by the network. Other four networks were established, but never as developed: Species and Specimens, Pollinators, Ecosystems, and Protected Areas. The I3N was Coordinated by the National Biological Information Infrastructure (NBII) of the United States Geological Survey (USGS) and funded through a Global Environmental Facility (GEF) project. A Focal Point in the National Government was nominated for each participating country, and the Coordinating Institution was supported by a Technical Working Group (TWG). A National Lead (and sometimes a Co-Lead) was defined for each country to take charge of technical and development issues. The main focus of the network was to standardize and share information and to build capacity for the management of invasive alien species in participating countries. Practical products were devised and developed, an I3N website with information and products for download, a national database template with an online interface, a risk assessment tool, a pathways assessment tool and a list server. The database was developed in full consistency with global data management initiatives on invasive species to ensure harmonization of vocabulary and definitions. Once the database template was ready, it was implemented in Brazil and Argentina first, then provided to more than twenty countries throughout Latin America and the Caribbean. This product was delivered with a training workshop hosted by the I3N in which technical, scientific and managerial information were provided, case studies were presented by locals, and one day was devoted to training on database use. At one point, 13 countries had national databases online. Of these, only four are functional to this day. The tools developed by I3n were distributed beyond the region of initial coverage through training provided for Association of Southeast Asian Nations (ASEAN), reaching ten countries in that region, and to different Caribbean states through the CABI Caribbean GEF project. The database was initially developed in Microsoft Access software in 2004. For reasons of copyright and costs, some countries were unable to implement the database in that format. A new version was developed in open-source software based on feedback from the users for improvement and released in 2011. The old versions were replaced country by country, with some technical assistance provided for installation and use, including manuals in English, Spanish, and Portuguese.

Why didn't the databases last in most countries? Mostly, because institutions in charge lacked specific mandates on invasive species, or for lack of expertise and/or lack of people working on biological invasions. Most databases hosted by national governments were lost after elections as technical staff were replaced. A few were hosted by universities or non-governmental organizations. The four databases that have persisted are managed by non-governmental organizations and universities. In each case, there is someone in charge keen to maintain and build on the work that has been done and because the data were deposited in an open-source repository. In most cases, unfortunately, people learned from the experience but were not able to carry on without specific funding or an official mandate. The risk assessment tools were used by some governments as a base to develop customized assessments. These initiatives were linked to other global programmes and represented the beginning of governance on invasive species in most countries in Latin America. The I3N network was discontinued when the GEF project that funded its work was terminated in 2011.

APFISN has been established as a response to the immense costs and dangers posed by invasive species to the sustainable management of forests in the Asia-Pacific region. It is a cooperative alliance of 34 member countries of the Asia-Pacific Forestry Commission (APFC). The network operates under the umbrella of APFC which is a statutory body of the Food and Agriculture Organization (FAO). The APFISN focuses on inter-country cooperation that helps to detect, prevent, monitor, eradicate and/or control forest invasive species in the Asia-Pacific region (Asia-Pacific Forest Invasive Species Network, 2021).

NOBANIS was established as a network between authorities of the region. The network was initiated with funding by the Nordic Council of Ministers. One of the main goals of NOBANIS is to provide tools for implementing the precautionary approach against the unintentional dispersal of invasive alien species. It also establishes regional cooperation to aid countries in eradication, control and mitigation of these species. The establishment of NOBANIS was a response to the recommendations that came out of the Convention of Biological Diversity (CBD) 6th meeting of the Conference of Parties (COP) in 2002. The NOBANIS has a national focal point in each of the participating countries.

CABI is an international non-profit organization that hosts a large number of invasive alien species-related projects linking different countries and rural communities, especially in Asia and Africa. CABI has developed the open access Invasive Species Compendium as an open access tool to support identification of invasive alien species globally.[11]

Acronyms

APFC	Asia-Pacific Forestry Commission
APFISN	Asia-Pacific Forest Invasive Species Network
ASEAN	Association of Southeast Asian Nations
CABI	Centre for Agriculture and Bioscience International
EASIN	European Alien Species Information Network
EICAT	Environmental Impact Classification for Alien Taxa
FAO	Food and Agriculture Organization (of the United Nations)
GEF	Global Environment Facility
GISD	Global Invasive Species Database
IABIN	Inter-American Biodiversity Information Network
ISC	Invasive Species Commission
ISSG	Invasive Species Specialist Group
IUCN	International Union for Conservation of Nature

[11] https://www.cabi.org/ISC

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