FERAL FUTURES: OVERVIEW OF TECHNOLOGY OPPORTUNITIES FOR VERTEBRATE PEST MANAGEMENT

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FOREWORD

Australia has a huge biosecurity and invasive species problem that undermines the nation's 2030 goals to both build a $100 billion agricultural industry and protect our globally important threatened species and biodiversity. Innovation will be critical to tackling this challenge, and a strategic technology pathway is needed to transform how our pests and weeds are managed by the end of the decade. Given the increasing risks and impacts, business as usual is simply not an option. This emerging technology pathway will propel Australia and New Zealand to a more technology enabled and integrated way of managing vertebrate pests efficiently at large scales.

Fortunately, science is driving this technology innovation at an increasingly rapid rate, with genetic and digital technologies poised to potentially transform our National Biosecurity System – including the way we manage new, emerging, and established vertebrate pests.

The Centre for Invasive Species Solutions is already playing a leading role in key technology areas through its collaborative member-based organisation that spans the Australian Government, all States and the ACT, industry Research and Development Corporations, CSIRO, NRM Regions Australia, universities, peak industry groups, conservation NGOs and the NZ government.

The full report – Invasive Species Solutions 2030 - Overview of Technology Opportunities - has been commissioned to provide an overview of these and other technology opportunities, in order to inform the technology pathway that could be pursued through the Centre's proposed *Invasive Species Solutions 2030* initiative. This special abridged version has also been published to inform the 18th Australasian Vertebrate Pests Conference, with its theme of *Feral Futures 2051*.

This report provides a window to a range of these technologies and the solutions able to be delivered to strengthen and transform vertebrate pest management by 2030 and beyond.

We commend it to you.

Bruce Christie
Chair

Andreas Glanznig
CEO

1 EXECUTIVE SUMMARY

Vertebrate pests usually include a diverse group of animals such as amphibians, reptiles, birds and mammals, and present a significant threat to Australia's biosecurity and biodiversity. The most common management options in Australia currently consist of exclusion barriers, biological control, manipulation of habitats, effective monitoring and culling. The report herein provides a landscape analysis of biosecurity technology opportunities that could be leveraged in effective management of vertebrate pest species.

The overview is framed around the Centre for Invasive Species Solutions (CISS) four innovation platforms and how they can be efficiently utilised to manage one of the focal invasive species streams: vertebrate pests. The four innovation platforms reviewed in this report are:

1. Surveillance technologies and systems
   - Genetic surveillance technologies
   - Artificial intelligence/machine learning-based surveillance technologies
2. Biocontrol technologies and systems
3. Integrated landscape management
4. Community engagement.

This study further reflects and provides commentary on current research activities in each of these platforms and provided commentary on their effectiveness and efficiency in reducing impacts of vertebrate pests to agriculture and the environment.

Multiple species of animals have been introduced to Australia over time, resulting in the establishment of numerous feral species across large geographic ranges.[1] Some species (e.g. fox and rabbit) were released into the wild as a consequence of early British settlement, whereas others (e.g. goat and pig) escaped domestication or captivity, and some (e.g. Indian myna[2]) were released illegally. Introduced animals, including rabbits, foxes, feral goats and feral pigs, have established large and widespread populations in Australia. Exotic animals that become established in the wild typically have a history of doing so in many places, and often have the following attributes:

- high fecundity
- generalised diet
- an ability to live in modified landscapes
- a climatic match between Australia and the place where they occur naturally.[3]

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[1] Animal Health Australia (AHA), *Megatrends, opportunities and challenges facing Australian livestock industries*, Prepared by Spiegare Pty Ltd, 2019, https://www.animalhealthaustralia.com.au/our-publications/industry-publications/megatrends-report/ (accessed 20/05/2020).

[2] Department of Primary Industries, Parks, Water and Environment (DPIPWE) -Tasmanian Government, 'Invasive birds: Indian Myna', *DPIPWE* [website], 7 February 2020, https://dpipwe.tas.gov.au/invasive-species/invasive-animals/invasive-birds/indian-myna (accessed 29/11/2020).

[3] Bomford, M. & Hart, Q., 'Non-indigenous vertebrates in Australia' in Pimental, D. (ed.), *Biological invasions: Economic and environmental costs of alien plant, animal, and microbe species*, CRC Press, Boca Raton, Florida, CRC Press, 2020, pp. 25-45.

A diverse range of introduced species live in Australia's land and water environments including rabbits, foxes, feral cats, deer and carp, and are commonly understood to have significant negative impact on ecological communities leading to extinction or decline of various native species. However, in some situations, native species such as the large macropodids – red kangaroos (*Osphranter rufus*) and eastern grey kangaroos (*Macropus giganteus*), and koala (*Phascolarctos cinereuscan*), become innumerable or 'overabundant' and cause significant damage to the environment.[4]

Among Australia's most notorious exotic vertebrate species are the common starling (*Sturnus vulgaris*), feral cat (*Felis catus*), European rabbit (*Oryctolagus cuniculus*), red fox (*Vulpes vulpes*), feral pig (*Sus scrofa*), feral goat (*Capra hircus*), house mouse (*Mus musculus*), cane toad (*Bufo marinus*), and black rat (*Rattus rattus*).[5] In Australia, pastoralism has also been associated with a large increase in artificial point water sources (i.e. dams). This increase in grasslands and water availability is linked to significant increases in macropod (kangaroo and wallaby) populations and densities.[6]

Section 2 of this report highlights the key megatrends with a focus on breakthrough technologies and attempts to understand the opportunities and features required to build a highly efficient biosecurity system. Following on, Section 3 discusses the outlook of a technology-led innovation focused National Biosecurity System. It also highlights how the integration of digital sensing and genetic developments should form the basis of 'Future Digital Farming' for better bio-surveillance, rapid detection and monitoring of pest species, leading to possible eradication and better preparedness. The subsequent sections – 4, 5, 6 and 7, examine the opportunities for the four innovation platforms identified by CISS and their role in efficient and effective management of vertebrate species. It should be noted that many of the technologies discussed in the review have their origin in military defence and intelligence and therefore we have been unable to include undisclosed new technologies in this review; it will however be important for CISS to be constantly vigilant on what emerges from this space. The final section – 8, discusses the findings of the report and how these will impact the management of both threats and ongoing impacts of vertebrate pests in Australia.

The report emphasises four key megatrends: intensification of climate variability, rapid urbanisation driven by population growth, global interconnectedness, and acceleration of technological advancements, playing an integral role in the effective management of vertebrate species.
The current toolbox for addressing vertebrate pests is incomplete and inadequate in many cases. New technologies such as gene editing are emerging; crossover applications are being found for existing technologies such as drones, nanosensors and nanosatellites; and multi-disciplinary approaches are proving highly potent for particularly complex and large-scale problems.

While CISS is looking at solutions for established pest species, there is a growing need to establish early warning systems for emerging vertebrate pests, leveraging these technological advancements and encouraging better community surveillance. Stronger focus needs to be placed on the development of products that will address local challenges and (coincidentally) have global impact. Innovation and investment in managing invasive species threats have historically been impeded by unclear value propositions for the proposed research and product solutions – a trend that needs to be addressed moving forward.

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[4] Fleming, P. et al., 'Invasive species and their impacts on agri-ecosystems: Issues and solutions for restoring ecosystem processes', *The Rangeland Journal*, vol. 39, 2017. https://doi.org/10.1071/RJ17046

[5] Invasive Species Specialist Group (ISSG), *ISSG* [website], n.d., http://www.issg.org/worst100_species.html (accessed 29/11/2020).

[6] Boom, K. et al., 'Pest and resource: A legal history of Australia's kangaroos', *Animal Studies Journal*, vol. 1, no. 1, 2012, pp. 17–40.

2 INTRODUCTION

Australia faces growing pressure from terrestrial and aquatic pests, weeds and diseases, which are posing serious threats to the country's biodiversity, ecosystem sustainability and economy.[7] The combined cost of managing, controlling invasive species and the resulting economic impact is estimated to be more than $13.6 billion dollars a year and is escalating everyday with new threats emerging.[8,9] For example, rabbits, goats and camels prevent native desert plant community regeneration; rabbits alone impacting over 320 threatened species.[10]

The pressures driving invasive species spread are unlikely to lessen in the coming decades. Environmental, social, technological and economic megatrends are likely to negatively impact Australia's biosecurity standing, and in turn, efforts to maintain that standing will require ever more sophisticated tools. It has become apparent through the observed convergence of biological, environmental and digital sciences in agricultural practices that a similar opportunity is presented to address invasive species in broader terms. The trans-disciplinary nature of the development and subsequent implementation of a range of solutions will require a more systematic and coordinated approach in the future, so as to drive rigorous development processes and community engagement.

Australian research and development stands well placed as a leading actor in the development of invasive species solutions, with a well developed, interdisciplinary science and engineering network and a nation that values biosecurity outcomes for its agriculture and environmental services sectors. This report reviews the latest technological development that has the potential to better manage invasive species in Australia and globally.

Notwithstanding that Australia's stringent biosecurity measures have dramatically slowed the number of new invasive species arriving, those already here have continued to spread and their cumulative effect is growing. Recent research highlights that 1,257 or 82% of Australia's threatened species are directly affected by 207 invasive plants, 57 animals and three pathogens.[11] The recent 2014 extinction of the Christmas Island forest skink due to invasive species highlights that they remain a major threat to Australian wildlife.[12]

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[7] CSIRO, *Australia's Biosecurity Future: Preparing for future biological challenges*, CSIRO, 2014, https://www.csiro.au/~/media/Do-Business/Files/Futures/Australias-Biosecurity-Future-executive-summary.pdf?la=en&hash=D854B0A6F740EEB0AFBEE94194450A2CC37413F0 (accessed 14/08/2020).

[8] Australian Academy of Science, 'Australia's silent invaders', *Australian Academy of Science* [website], 2020, https://www.science.org.au/curious/earth-environment/invasive-species#:~:text=The%20combined%20cost%20of%20invasive,biggest%20environmental%20problems%20facing%20Australia (accessed 14/08/2020).

[9] Hoffmann, B. & Broadhurst, L., 'The economic cost of managing invasive species in Australia', *NeoBiota*, vol. 31, 2016, pp.1–18. https://doi.org/10.3897/neobiota.31.6960

[10] Kearney, S. G. et al., 'The threats to Australia's imperilled species and implications for a national conservation response', *Pacific Conservation Biology*, vol. 25, 2018, pp. 231–244. https://doi.org/10.1071/PC18024_CO

[11] Kearney, S. G. et al., 2018.

[12] Andrew, P. et al., 'Somewhat saved: A captive breeding programme for two endemic Christmas Island lizard species, now extinct in the wild', *Oryx: the journal of the Fauna Preservation Society*, vol. 52, no. 1, 2018, pp. 171–174. https://doi.org/10.1017/S0030605316001071

Management of invasive species is usually divided into four categories across an invasion curve (Figure 1). The most cost-effective way to reduce impacts of invasive species is to prevent them from establishing in the first place. Complete removal of an invasive species may be possible if we detect it soon after its introduction and immediately take steps to eradicate it. 'Early detection and rapid response' (EDRR) can be effective, but it is more costly than prevention. Complete eradication becomes increasingly unlikely as populations grow and intense efforts are necessary to contain the core population of a species and eradicate it from new areas. Long-term management aims to reduce populations to the lowest feasible levels and to protect specific highly valued resources.[13,14]

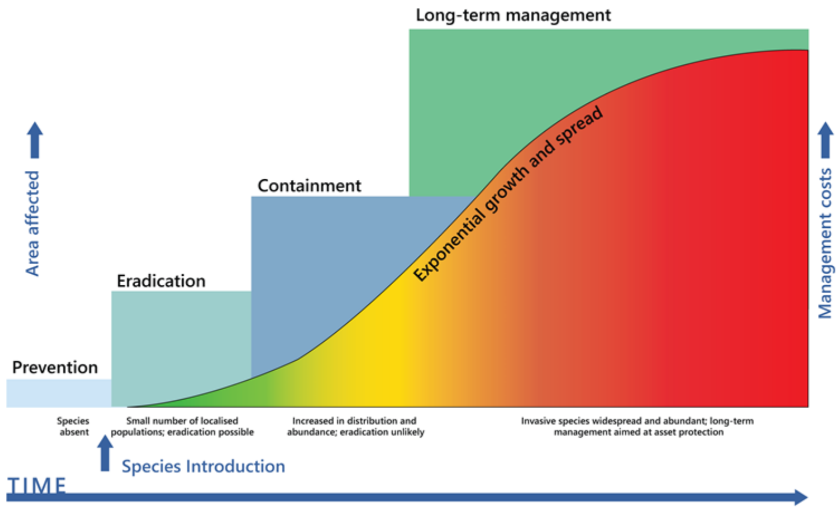

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Figure 1. The invasion curve.

Source: Adapted from *Invasive Plants and Animals Policy Framework*, Melbourne, Australia, Department of Primary Industries, The State of Victoria, 2010, fig. 2. https://agriculture.vic.gov.au/data/assets/pdf_file/0009/582255/Invasive-Plants-and-Animals-Policy-Framework-IPAPF.pdf (accessed 27/11/2020).

Rapid agricultural expansion and intensification, population shift from rural to urban areas, changing consumer sentiment and expectations, globalisation of trade and travel, increased biodiversity pressures, and declining natural resources, are leading to a future where current processes and practices relating to efficient management of invasive species and effective maintenance of biosecurity are not adequate. Hence, continuing improvement of existing pest management practices and novel approaches are inherently required to address public concerns about animal welfare, adherence to stringent trade requirements, and successfully respond to a growing threat of incurring resistance to existing pesticides as well as, possibly, biological control agents. The focus needs to be shifted on developing effective surveillance and pest monitoring techniques to increase the chances of early interception of invasive species or to confirm their eradication.

[13] Schmiedel, D. et al., 'Evaluation system for management measures of invasive alien species', *Biodivers. Conserv.,* vol. 25, 2016, pp. 357–374. https://doi.org/10.1007/s10531-016-1054-5

[14] Tobin, P. C., 'Managing invasive species', [version 1; peer review: 2 approved], *F1000Research*, vol. *7*, 2018, F1000 Faculty Rev.: 1686. https://doi.org/10.12688/f1000research.15414.1

2.1 INTRODUCTION OF TRENDS AND TECHNOLOGY DISRUPTION

Megatrends are major shifts in environmental, social and economic conditions occurring at the intersection of many trends.[15] Megatrends have the potential to irreversibly change the way we live and challenge the models we use to organise our societies.[16] A range of authors and organisations around the world have undertaken studies to identify megatrends.[17,18,19,20,21,22] While the names and classifications of megatrends can differ, common themes have emerged across the literature, each with the potential to significantly influence Australia's management of invasive species. These themes include growing populations; increasing urbanisation; demographic societal and geographic climate change impacts; rapid acceleration of technology development; globalised trade yet increasing geo-political trading complexity; increasing trade regulation; increasing consumer demand for eco-friendly products; and highly stressed natural resource systems.

Highlighted below are implications from four key megatrends that are likely to escalate pressure on invasive species management, with the potential to bring about significant change and complexity for Australia's biosecurity future:

I. **Climate change intensifies**

- Rising temperatures, reduced rainfall and increased frequency of extreme weather events will (among other things) contribute to a loss of biodiversity, lead to reduced water resources and increase instances of soil erosion consequently increasing the vulnerability of our natural ecosystem to pests and diseases.
- Mass disruption of natural habitats and changing climatic conditions will cause significant changes in disease vector and feral animal distribution and proximity to farmed animals, thereby increasing biosecurity risks to animal and aquaculture health.
- Changes in climatic conditions will increase the risk of incursion, the subsequent establishment of new disease vectors and the re-distribution of feral animal intermediate hosts, increasing the pressure on our biosecurity system, in particular national border control and surveillance.

II. **Rapid population growth accelerating urbanisation**

- Through growing food demand and urban encroachment, land use will become more competitive, placing greater pressure on the natural environment.
- The ongoing expansion of our cities will continue to change interactions between humans, flora and fauna, agriculture and disease vectors, thus escalating the risks of zoonotic disease.

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[15] Hajkowicz, S., *Global Megatrends: Seven patterns of change shaping our future*, Australia, CSIRO Publishing, 2015.

[16] Hajkowicz, S. & Eady, S., *Rural Industry Futures: Megatrends impacting Australian agriculture over the coming twenty years,* Canberra, Rural Industries Research and Development Corporation (RIRDC), 2015.

[17] EYGM Ltd, *Megatrends 2015: Making sense of a world in motion*, 2015, https://www.ey.com/Publication/vwLUAssets/ey-megatrends-report-2015/$FILE/ey-megatrends-report-2015.pdf (accessed 18/05/2020).

[18] CSIRO Futures, *Food and Agribusiness Roadmap: Unlocking value-adding growth opportunities for Australia*, Australia, CSIRO, 2017, https://www.csiro.au/en/Do-business/Futures/Reports/Food-and-Agribusiness-Roadmap (accessed 20/05/2020).

[19] National Farmers' Federation (NFF), '2030 Roadmap: Australian agriculture's plan for a $100 billion Industry'*, NFF*, [website], 17 October 2018, https://www.nff.org.au/read/6187/nff-releases-2030-roadmap-guide-industry.html (accessed 20/05/2020).

[20] Price Waterhouse Coopers (PWC) UK, 'Shift in global economic power', *PWC UK*, [website], 2019, https://www.pwc.co.uk/issues/megatrends/shift-in-global-economic-power.html (accessed 20/05/2020).

[21] Butler, J. et al., *Megatrends: Agriculture and food,* Report prepared by the Australia-Indonesia Centre, Monash University, Australia, CSIRO, 2015.

[22] Animal Health Australia (AHA), *Megatrends, opportunities and challenges facing Australian livestock industries*, Report prepared by Spiegare Pty Ltd, 2019, https://www.animalhealthaustralia.com.au/our-publications/industry-publications/megatrends-report/ (accessed 20/05/2020).

- The loss of agricultural diversity due to rapid urbanisation can create food security risks in the event of a pest or disease outbreak.
- Changing consumer expectations will require new and adaptive biosecurity management capabilities.

III. Global interconnectedness and trade dependency

- With rising trade movement and continued growth in international visitors, Australia will continue to face significant risk of incursion of pests and infectious diseases.
- Greater domestic freight movements will also enable pests and diseases to spread within Australia unless proper surveillance system is implemented.
- Online retailing will increase the risk of introduction of pests and diseases.
- International trade awareness is becoming more complex and non-tariff trade measures and political and trade positioning in some markets is becoming more complex.

IV. Rise of disruptive technologies[23]

- Big data and remote sensing technologies will continue to increase resource efficiency. Improved use of GPS technology and IoT technologies could enable faster detection and improved responses to environmental issues and adverse events.
- Industrial progression and improvement across surveillance and monitoring technologies, big data and analytics, genetics and synthetic biology, and smarter devices supported by improvements in Internet of Things (IOT), will take a lead in addressing future invasive species management challenges.
- New communication tools, as well as social media platforms, will help to enhance information flow and better engage the wider community, including citizen scientists, to play a critical role in biosecurity management.

2.1.1 Rise of disruptive technologies as the central megatrend

Rapid acceleration of technology is **the central megatrend** that will continue to be an integral part of managing livestock and crops, and native species and conserving biodiversity in many countries across the world. The current toolbox for addressing invasive species is incomplete and inadequate in many cases. New technologies such as gene editing are emerging, crossover applications are being found for existing technologies such as drones, nanosensors and nanosatellites, and multi-disciplinary approaches are proving highly potent for particularly complex and large-scale problems.[24]

High spatial and spectral resolution sensors, particularly airborne imaging spectroscopy, have demonstrated promise to map plant species based on their particular distinctive spectral features in the visible to shortwave infrared spectrum, and even with thermal infrared spectrometers either on single images or through seasonal and inter-annual changes.[25,26] Other technologies like LiDAR (Light Detection and Ranging) show promise for differentiating species based on 3D crown structure

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[23] Disruptive technologies such as gene editing and gene drive or nanosatellite developments typically demonstrate a rapid rate of change in capabilities in terms of price/performance relative to substitutes and alternative approaches, or they experience breakthroughs that drive accelerated rates of change or discontinuous capability improvements. Manyika, J. et al., *Disruptive technologies: Advances that will transform life, business, and the global economy*, Mckinsey Global Institute, 2013. https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/Disruptive%20technologies/MGI_Disruptive_technologies_Full_report_May2013.pdf (accessed 16/02/2021).

[24] Martinez, B. et al., 'Technology innovation: Advancing capacities for the early detection of and rapid response to invasive species', *Biol. Invasions,* vol. 22, 2020, pp. 75–100. https://doi.org/10.1007/s10530-019-02146-y

[25] Laybros, A. et al., 'Across date species detection using airborne imaging spectroscopy', *Remote Sense.*, vol. 11, no. 7, 2019, p. 789. https://doi.org/10.3390/rs11070789

[26] Kagan, P. et al., 'Multispectral approach for identifying invasive plant species based on flowering phenology characteristics', *Remote Sense.*, vol. 11, 2019. https://dio.org/ 10.3390/rs11080953

and spatial characteristics.[27,28] Synergistic use of these technologies has promise for improved surveillance of invasive plant species and their impacts on the ecosystems they invade. Several imaging spectrometer satellites that represent the most advanced technology, have promise for invasive species mapping and are currently under development or planned for later in this decade, e.g. the EnMAP, PRISMA, HISUI, and others.[29] NASA's proposed HyspIRI imaging spectrometer and multiband thermal imager shows promise to measure and monitor global changes in invasive species at relatively high spatial (30m) and temporal (16-day repeat) scales.[30] Satellites such as Landsat 8 and European Sentinel 2a and 2b provide advanced multispectral imagers with frequent global coverage and weekly repeat cycles, and also contribute to the suite of new instrument capabilities for monitoring plant invasions.[31] Commercial satellites are delivering increased resolution from 5 m to 3 m (with the next generation real-time 3 m satellite data), to 50 cm with 15 SkySat imagery satellites with options of 4-band, 5-band and 8-band imagery that has tasking capability.[32]

The technologies discussed have tremendous potential to be transferred effectively to the animal domain. For example, deployment of LiDAR to improve biodiversity in Yellowstone National Park USA is already underway.[33] In addition, introduced spotted deer and elephants in the Andaman Islands have been detected by determining the changes in vegetation growths. Using a normalised difference vegetation index (NDVI) from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data, areas of vegetation vulnerability were determined by measuring the varying degree of vegetation growth in the region.[34] Notably, large animals maybe also detected using freely available optical imagery from instruments onboard Landsat (30 m resolution), Moderate Resolution Imaging Spectroradiometer (MODIS, 250–1000 m resolution), or other multispectral instruments.[35]

The advent of UAV (unmanned aerial vehicle) or 'drone' technology has created the promise of a revolution in data collection methods for biodiversity conservation that could address many of the constraints imposed by on-the-ground fieldwork. Wildlife biologists are attempting to adopt this new technology to address a wide range of questions and problems in native species management.[36,37] Machine learning approaches have also been applied to ecological problems and have been widely adopted to identify the complex structure of datasets, and to train risk prediction models in ecology.[38]

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[27] Hastings, J. et al., 'Tree species traits determine the success of LiDAR-based crown mapping in a mixed temperate forest', *Remote Sense.,* vol. 12, 2020, p. 309. https://dio.org/10.3390/rs12020309.

[28] CISION, 'AGERpoint™ announces development of cost effective mobile LiDAR sensor', *CISION PRNewswire* [website], 3 April 2017, https://www.prnewswire.com/news-releases/agerpoint-announces-development-of-cost-effective-mobile-lidar-sensor-300433066.html (accessed 20/08/2020).

[29] Transon, J. et al., 'Survey of hyperspectral earth observation applications from space in the Sentinel-2 context', *Remote Sense.*, vol. 10, no. 2, 2018, p.157. https://doi.org/10.3390/rs10020157

[30] Transon, J. et al., 2018.

[31] Transon, J. et al., 2018.

[32] Planet, 'The entire earth, every day', *Planet* [website], 2020, https://www.planet.com/products/planet-imagery/ (accessed 20/08/2020).

[33] FindLight, 'Using LIDAR to improve biodiversity in Yellowstone National Park', *FindLight* [website], 8 June 2018, https://www.findlight.net/blog/2018/06/08/lidar-improve-biodiversity-yellowstone/ (accessed 17/02/2021).

[34] Ali, R., & Pelkey, N., 'Satellite images indicate vegetation degradation due to invasive herbivores in the Andaman Islands', *Current Science*, vol. 105, no. 2, 2013, pp. 209-214. http://www.jstor.org/stable/24092640

[35] Cassidy, E., 'Sensing invasive species from Space', *EarthData–NASA* [website], 22 May 2020, https://earthdata.nasa.gov/learn/articles/sensing-invasive-species (accessed 16/02/2021).

[36] Rominger, K. & Meyer, S. E., 'Application of UAV-based methodology for census of an endangered plant species in a fragile habitat', *Remote Sens.,* vol. 11, no. 6, 2019, p. 719. https://doi.org/10.3390/rs11060719

[37] Alvarez-Taboada, F., Paredes, C. & Julián-Pelaz, J., 'Mapping of the invasive species *Hakea sericea* using unmanned aerial vehicle (UAV) and WorldView-2 imagery and an object-oriented approach', *Remote Sens.,* vol. 9, no. 9, 2017, p. 913. https://doi.org/10.3390/rs9090913

[38] Erdoğan, Z. & Namli, E., 'A living environment prediction model using ensemble machine learning techniques based on quality of life index', *J. Ambient Intell. Human Comput.*, 2019. https://doi.org/10.1007/s12652-019-01432-w

Artificial neural networks have been applied to monitor and predict the density of invasive species and have been also efficiently used as a tool to suggest eradication strategies.[39,40,41]

UAVs, popularly called drones, have their heritage within military defence, and until recently their development was predominantly driven by defence applications, but the adaptability of UAVs are now allowing these to be increasingly used for biosecurity purposes.[42] Historical examples include US military developed GPS technology, but future examples potentially include nano drone swarms that could further transform biosecurity surveillance.[43,44,45]

The rapid pace of technology advancement in the field of genetics is giving rise to approaches for the eradication and control of invasive species. Work is already underway to investigate advanced biotechnology applications for public health, pest management and biodiversity conservation, all of which show a range of possibilities for addressing invasive species.[46,47] Cas9 has been used to create gene drives in which acquisition of a trait and the Cas9 machinery are coupled to ensure rapid trait propagation through a population. Specifically, gene drives have been used in *Anopheles gambiae,* the mosquito vector for malaria, to drive a recessive female sterility genotype with transmission to progeny rates exceeding 90%; this has the potential to suppress the spread of malaria in humans.[48] Likewise, anti-*Plasmodium falciparum* CRISPR systems have been implemented in the Asian malaria vector *Anopheles stephensi.*[49,50]

Notwithstanding the potential of CRISPR-based gene drives for controlling the spread of disease vectors, as with any nascent technology, successful implementation on a broad scale will require both scientific advancement (notably biological containment and drive efficiency) as well as regulatory approval and public acceptance.[51] RNA interference technologies have also been widely implemented to improve targeted pest and invasive species control and to replace certain use patterns of conventional and organic chemistries used for broad-spectrum pest control. RNAi has been successfully demonstrated to act as a stable biopesticide by using prey species as vectors for transmission.[52] It should be noted that vertebrates such as rodents may also digest RNA

[39] Xiao, Y., Greiner, R. & Lewis, M. A., 'Evaluation of machine learning methods for predicting eradication of aquatic invasive species', *Biol. Invasions,* vol. 20, 2018, pp. 2485–2503. https://doi.org/10.1007/s10530-018-1715-2

[40] Tabak, M. A. et al., 'Machine learning to classify animal species in camera trap images: Applications in ecology', *Methods Ecol. Evol*., vol. 10, no. 4, 2019, pp. 585–590. https://doi.org/10.1111/2041-210X.13120

[41] Sandino, J. et al., 'UAVs and machine learning revolutionising invasive grass and vegetation surveys in remote arid lands', *Sensors*, vol. 18, no. 2, 2018, p. 605. https://doi.org/10.3390/s18020605

[42] Peters, J., 'Watch DARPA test out a swarm of drones', *The Verge* [website], 9 August 2019, https://www.theverge.com/2019/8/9/20799148/darpa-drones-robots-swarm-military-test (accessed 02/10/2020).

[43] Kallenborn, Z., 'The era of the drone swarm is coming, and we need to be ready for it', *Modern War Institute* [website], 25 October 2018, https://mwi.usma.edu/era-drone-swarm-coming-need-ready/ (accessed 02/10/2020).

[44] Schilling, F. et al., 'Learning vision-based cohesive flight in drone swarms', *arXiv*:1809.00543, 2018, Cornell University. https://arxiv.org/abs/1809.00543 (accessed 02/10/2020).

[45] Tahir, A. et al., 'Swarms of unmanned aerial vehicles: A survey', *Journal of Industrial Information Integration*, vol. 16, 2019. https://doi.org/10.1016/j.jii.2019.100106.

[46] Harvey-Samuel, T., Ant, T. & Alphey, L., 'Towards the genetic control of invasive species', *Biol. Invasions*, vol. 19, 2017, pp. 1683–1703. https://doi.org/10.1007/s10530-017-1384-6

[47] Piaggio, A.J. et al., 'Is it time for synthetic biodiversity conservation?', *Trends Ecol. Evol*., vol. 32, no. 2, 2017, pp. 97–107. https://doi.org/10.1016/j.tree.2016.10.016

[48] Simoni, A. et al., 'A male-biased sex-distorter gene drive for the human malaria vector *Anopheles gambiae*', *Nat. Biotechnol*., vol. 38, 2020, pp. 1054–1060. https://doi.org/10.1038/s41587-020-0508-1

[49] Barrangou, R. & Doudna, J., 'Applications of CRISPR technologies in research and beyond', *Nat. Biotechnol.*, vol. 34, no. 9, 2016, pp. 933–941. https://doi.org/10.1038/nbt.3659

[50] Moro, D. et al., 'Identifying knowledge gaps for gene drive research to control invasive animal species: The next CRISPR step', *Global Ecol. Conserv*., vol. 13, 2018, e00363. https://doi.org/10.1016/j.gecco.2017.e00363

[51] Martinez, B. et al., *Advancing federal capacities for the early detection of and rapid response to invasive species through technology innovation*, Washington, D.C., National Invasive Species Council Secretariat, 2018.

[52] Lim, Z. X. et al, 'Diet-delivered RNAi in *Helicoverpa armigera:* Progresses and challenges', *Journal of Insect Physiology,* vol. 85, 2016, pp. 86–93. http://dx.doi.org/10.1016/j.jinsphys.2015.11.005

nanoparticles, which may possibly serve as a delivery vehicle.[53] The fundamental mechanism of a CRISPR–Cas9-mediated gene drive has now been demonstrated feasible in mice.[54] Managing landscape-scale environmental problems, such as biological invasions, can be facilitated by integrating realistic geospatial models with user-friendly interfaces that stakeholders can use to make critical management decisions.[55] Another key area where technological advancement can improve planetary life is strong community engagement. Technologies bridge the gap not only between amateurs and professionals, but also often overlooked communities, including indigenous peoples, rural communities and tourists, and enables everyone to play an important role in conservation.[56]

2.2 OPPORTUNITIES FOR AN INNOVATION-CENTRED TRANSFORMATION OF THE NATIONAL BIOSECURITY SYSTEM

Demonstrating ex ante benefits from biosecurity investment is often difficult as investment is based on perceptions and assessments of risk and impact, commonly with limited future regard to incursion detection response and research response timeframes. For example, the *Risk-Return Resource Allocation* (RRRA) project by the Centre of Excellence for Biosecurity Risk Analysis (CEBRA) provides a framework for the Australian Department of Agriculture, Water and the Environment to make resource allocation decisions that account for biosecurity risk.[57,58]

An innovation-centred transformation of the national biosecurity system is required that in the longer term shifts finite skills and resources from tactical response to strategic investment. The legacy impact of thoughtful and prudent strategic investment is that the potential economic or public amenity losses are reduced and timeframes for rectification and long-term production or amenity impacts are reduced (Figure 2). Technologies that deliver increased speed and specificity of detection at reduced cost and reduce the time for adoption of functional and cost-effective response measures will deliver long-term legacy impacts, and economic and positive public response through environmental amenity.

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[53] Campbell, K. J. et al., 'The next generation of rodent eradications: Innovative technologies and tools to improve species specificity and increase their feasibility on islands', *Biol. Conserv.*, vol. 185, 2015, pp. 47–58. https://doi.org/10.1016/j.biocon.2014.10.016

[54] Grunwald, H. A. et al., 'Super-Mendelian inheritance mediated by CRISPR–Cas9 in the female mouse germline', *Nature*, vol. 566, 2019, pp. 105–109. https://doi.org/10.1038/s41586-019-0875-2

[55] Tonini, F. et al., 'Tangible geospatial modeling for collaborative solutions to invasive species management', *Environmental Modelling & Software*, vol. 92, 2017, pp. 176–188. https://doi.org/10.1016/j.envsoft.2017.02.020.

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[58] Kompas, T. et al., 'Budgeting and portfolio allocation for biosecurity measures', *Aust. J. Agric. Resour. Econ.*, vol. 63, 2019, pp. 412–438. https://doi.org/10.1111/1467-8489.12305

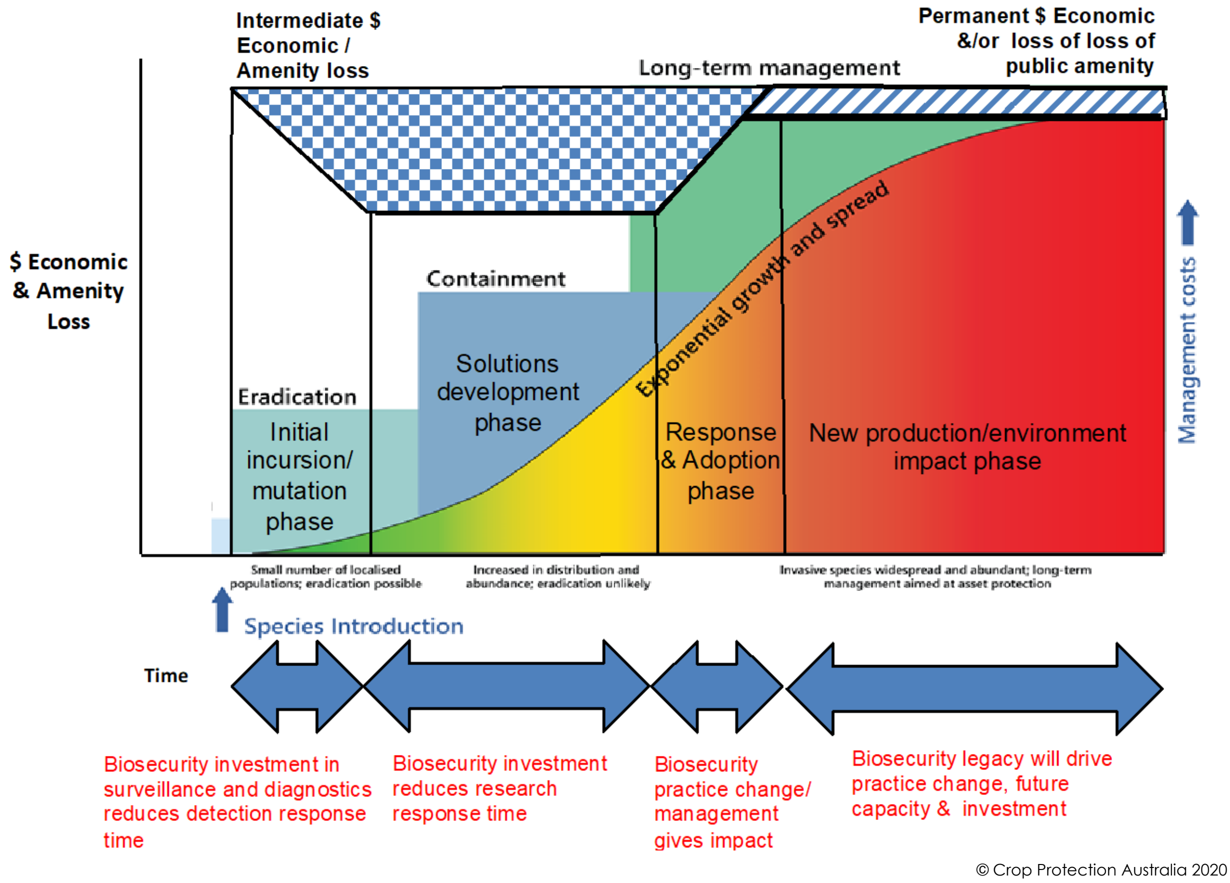

Figure 2. Value proposition for pre-emptive biosecurity investment and legacy impacts.

Source: Rainbow, R., Crop Protection Australia, 2020

2.3 NEEDS AND DESIRED FEATURES OF THE SYSTEM

An innovative biosecurity system should be seeking to invest in the development and demonstration of products that meaningfully impact economic, environmental and social outcomes. Biosecurity risks, threats and hazards should be managed in a data-driven surveillance analysis and action cycle as suggested below (Figure 3).[59]

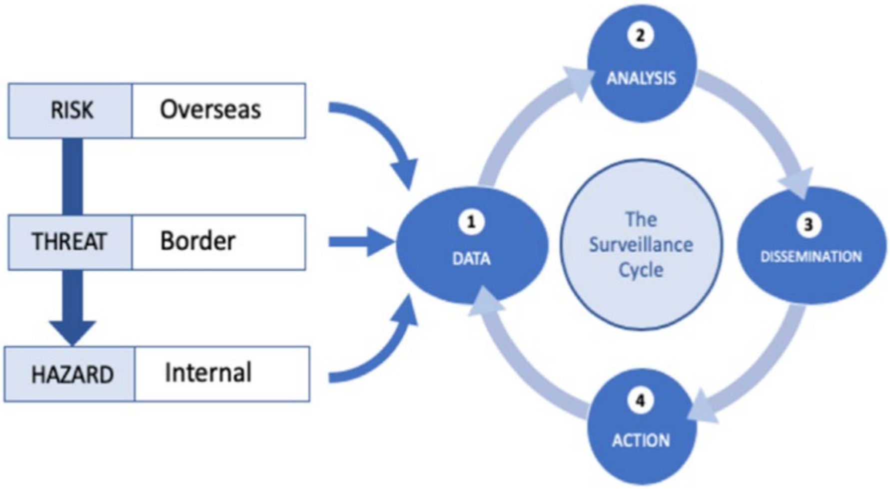

Figure 3. The role of emerging technologies on biosecurity system.

Source: Animal Health Australia (AHA), *Megatrends, opportunities and challenges facing Australian livestock industries*, Report prepared by Spiegare Pty Ltd, 2019, fig. 7, https://www.animalhealthaustralia.com.au/our-publications/industry-publications/megatrends-report/ (accessed 20/05/2020).

Recent advances in biomaterials and engineering research, together with big data computing and digital technologies, are being integrated for enhanced data collection and analysis that will play a transformational role in invasive species management. These systems can provide a step-change for biosecurity by being designed to monitor animal and habitat health, and amongst other things, automatically collect diagnostic data, provide real-time data analysis, enable rapid dissemination of intelligence, and inform timely decision-making around biosecurity response actions.

With regard to biosecurity, the systems in the past, present, and potentially in the future, highlight the value from the convergence of advanced technologies (goods/knowledge) and skills (services) which should combine in unique ways to address biosecurity challenges. The schematic developed below accords with the recently published report on the role of emerging technologies on Australian biosecurity system (Figure 4).[60]

[59] Animal Health Australia (AHA), *Megatrends, opportunities and challenges facing Australian livestock industries*, Report prepared by Spiegare Pty Ltd, 2019, https://www.animalhealthaustralia.com.au/our-publications/industry-publications/megatrends-report/ (accessed 20/05/2020).

[60] Animal Health Australia (AHA), 2019.

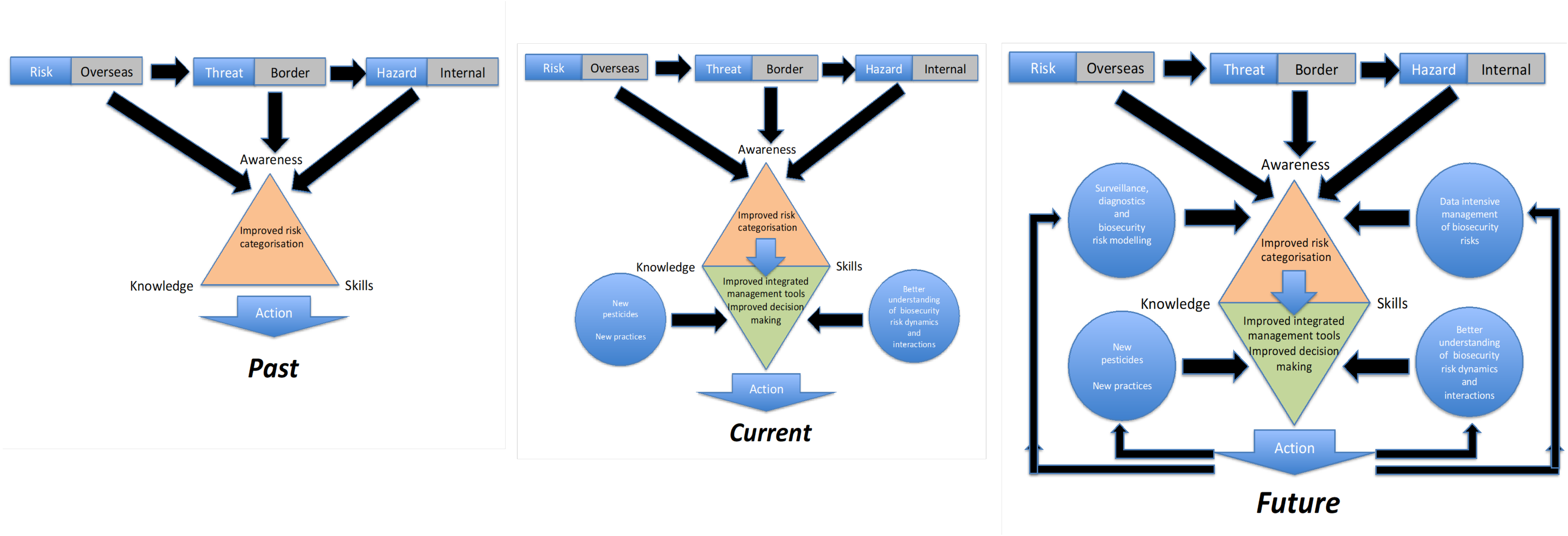

Figure 4. The role of technology and innovation in an advanced biosecurity system.

Source: Rainbow, R., Crop Protection Australia, 2020

Future biosecurity systems in the coming decades will be based on data intensive diagnostic surveillance incorporating real-time risk modelling for the management of security risks. This real-time capability will be underpinned by new sensors and field data connectivity systems built on a platform that incorporates interoperable data standards. The need for open data standards is a major issue identified more broadly in agriculture.[61] The integration of an innovative biosecurity system with agricultural data management network will be a critical element for enhancing effective biosecurity management. (See Section 3.1 Figure 6). Development of these data standards will also drive greater local and international investment into Australian needs through the scale of opportunity from all agricultural industries and landscape managers using common and universally compatible approach. Supporting the delivery of products to meet biosecurity challenges in a vibrant innovation ecosystem. The role that CISS and its partners play in that ecosystem and the means through which they coordinate and resource their efforts should also bear further consideration, as a constrained or suboptimal innovation ecosystem will inherently constrain the pathway to effective solutions.

2.4 SCOPE OF REPORT

CISS sought an overview of technological opportunities that currently exists to better manage future threat from vertebrate pest species in Australia.

CISS has framed its strategic RD&E direction around four innovation platforms which are:

1. Surveillance technologies and systems
   - Genetic surveillance technologies
   - Artificial intelligence/machine learning-based surveillance technologies
2. Biocontrol technologies and systems
3. Integrated landscape management
4. Community engagement.

This study will reflect on current research activity in each of these platforms and provide commentary on their effectiveness and efficiency in reducing the impacts of vertebrate pest species to Australian agriculture, biosecurity, and the overall environment.

Section 2 of the report, as seen above, highlights the key megatrends with a focus on disruptive technologies and attempts to understand the opportunities and features required to build a highly efficient biosecurity system. Following on, Section 3 discusses the outlook of a technology-led innovation focused National Biosecurity System. It also highlights how the integration of digital sensing and genetic developments should form the basis of 'Future Digital Farming' for better bio-surveillance, rapid detection and monitoring of pest species, leading to possible eradication and better preparedness. The subsequent sections – 4, 5, 6 and 7, examine the opportunities for the four innovation platforms identified by CISS and their role in efficient and effective management of vertebrate species. It should be noted that many of the technologies discussed in the review have their origin in military defence and intelligence and therefore we have been unable to include undisclosed new technologies in this review; it will however be important for CISS to be constantly vigilant on what emerges from this space. The final section – 8, discusses the findings of the report and how these will impact the management of threats and ongoing impacts of vertebrate pests in Australia.

[61] Leonard, E., Rainbow, R., & Trindall, J. (eds) et al., *Accelerating precision agriculture to decision agriculture: Enabling digital agriculture in Australia,* Cotton Research and Development Corporation (CRDC), Australia, 2017. https://www.crdc.com.au/sites/default/files/CRD18001-001 CRDC P2D Report low res.pdf (accessed 20/05/2020).

3 CONTEXT: TECHNOLOGY DISRUPTION, TRENDS AND FUTURES

3.1 AUTOMATED / COMMUNITY-PRODUCER GENERAL SURVEILLANCE /REAL-TIME DETECTION AND FEEDBACK LOOPS

For any organisation to successfully implement digital data technologies into their business, it is essential that this is delivered in a way that builds trust; trust both in terms of confidence in the findings and recommendations from the use of digital data tools, and also confidence that ownership, access and transfer rights are maintained by the individual producer.

Delivering long-term confidence to all stakeholders, both in production systems and environmental management using a transparent data, scientific evidence-based approach, is a critical legacy of a successful biosecurity system. There needs to be a transparent production industry policy, supported through education and understanding of the community to build that trust. As evidence grows that informed data-based decision-making and practice change results in increased profitability or environmental amenity, the trust in the data and mechanisms will increase (Figure 5).

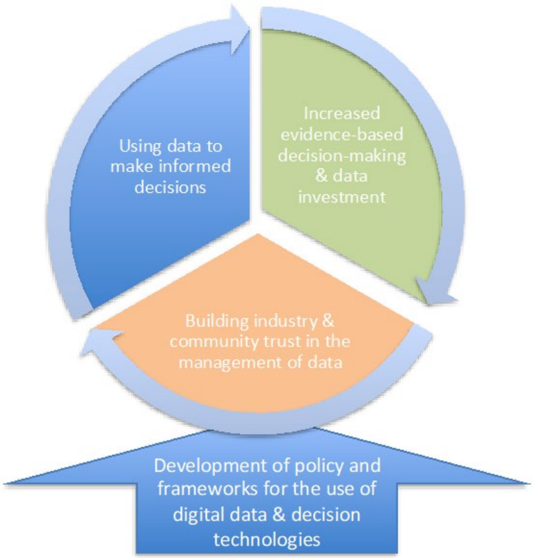

Figure 5. Key components that underpin informed decision making using digital data.

Source: Rainbow, R., Crop Protection Australia, 2020.

There are many components of a functioning digital data decision system that all need to work together to deliver biosecurity-supporting productivity and environmental sustainability outcomes (Figure 6).

Figure 6. Components of a functioning digital data decision systems that deliver impact.

Source: Rainbow, R., Crop Protection Australia, 2017.

The challenge is building all these components concurrently as a functional system. It is essential that common standards and cross-compatibility are established to enable a modular but functional interaction between the components within a sector or amongst adjacent sectors (such as environment and agriculture).

Digital sensor and data collection systems offer a robust and objective solution to conduct biosecurity surveillance. Sentinel surveillance systems (e.g. *iMapPests*[62]) are an example of innovative technology undergoing development that can significantly improve on-farm pest management through rapid and precise monitoring and reporting of airborne pests and diseases. Using animal heat signatures and size, it is technically possible to monitor production,[63] native,[64] and pest animals,[65] using aerial imagery UAVs or even satellite technology in real time; this however comes at a significant cost. The challenge of these systems is demonstrating value and trust in their use.

[62] iMapPESTS, 'iMapPESTS: Sentinel surveillance for agriculture', *iMapPESTS* [website], n.d., https://www.imappests.com.au/ (accessed 20/08/2020).

[63] CSIRO, 'Ceres Tag: Smart ear tags for livestock', *CSIRO* [website], 12 June 2020, https://www.csiro.au/en/Research/AF/Areas/Livestock/Ceres-Tag (accessed 20/08/2020).

[64] Perras, M. & Nebel, S., 'Satellite telemetry and its impact on the study of animal migration', *The Nature Education Knowledge Project* [website], 2012, https://www.nature.com/scitable/knowledge/library/satellite-telemetry-and-its-impact-on-the-94842487/ (accessed 20/08/2020).

[65] Colquhoun, L., 'Space the next frontier (for tracking feral buffalos', *CDO Trends* [website], 8 June 2020, https://www.cdotrends.com/story/14876/space-next-frontier-tracking-feral-buffalos (accessed 20/08/2020).

3.2 DIGITAL SENSING AND PLATFORMS

Over the last decade, remote sensing has offered many important contributions to the progress of invasion science, including improving our understanding of the drivers, processes, patterns, and impacts of invasive species.[66,67] Remote sensing has been particularly useful in identifying and mapping animal and plant invaders,[68,69] as well as predicting their current and future potential distributions and impacts.[70] Remote sensing applications have been rapidly developing in the arena of invasions, and as technology evolves it is also becoming a prominent tool to manage alien species (and invaded areas) and their impacts.[71]

The use of LiDAR technology (e.g. Riegl laser scanner) and hyperspectral sensors, either on satellites (e.g. *ALI* in *EO-1 Hyperion*), airborne vehicles (e.g. *CASI* sensor), or hand/boom-mounted structures (e.g. *CropScan*), has been particularly useful.[72] Also, when included in statistical modelling approaches, remote sensing data can be used to detect species able to escape from cultivation sites and to predict their potential areas of invasion.[73]

Understanding feedback loops between soil biota and alien species is emerging as a pressing issue in invasion ecology.[74] The field of soil remote sensing has been progressing greatly over the last decades. Modern remote sensing offers many approaches in monitoring soil parameters, including texture (through hyperspectral sensors), surface temperature (using thermal infrared bands), moisture (via passive microwaves), and roughness (using active sensors like synthetic radar or scatterometer sensors.[75] When properly calibrated with field measurements and applied in well-adjusted models, remotely sensed soil indices can provide fine-scale (and almost real-time) information on belowground-aboveground interactions.[76]

Satellite missions – besides tracking invasives – have the potential to further enhance ecological research on invasive species by generating datasets which can be used to study species' habitats and their likely distribution. New high-resolution datasets will enable researchers to understand climate and environmental parameters in unprecedented detail, which will in turn allow development of precision scale habitat suitability models. An example of such technology is *Multi-Scale Ultra High Resolution Sea Surface Temperature* (MUR SST) data from NASA's *Physical Oceanography Distributed Active Archive Center* (PO.DAAC), which has now attained a 1 km resolution,[77] and has the ability to deliver detailed information on habitat suitability for aquatic species. Additionally, for habitats of terrestrial species, NASA's *Soil Moisture Active Passive* (SMAP) mission offers readily

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[66] Juanes, F., 'Visual and acoustic sensors for early detection of biological invasions: Current uses and future potential', *J. Nat. Conserv*. vol. 42, 2018, pp. 7–11. https://doi.org/10.1016/j.jnc.2018.01.003

[67] Vaz, A. S. et al., 'Managing plant invasions through the lens of remote sensing: A review of progress and the way forward', *Sci. Total Environ.*, vol. 642, 2018, pp. 1328–1339. https://doi.org/10.1016/j.scitotenv.2018.06.134

[68] Müllerová, J. et al., 'Unmanned aircraft in nature conservation: An example from plant invasions', *Int. J. Remote Sens.*, vol. 38, 2017, pp. 2177–2198. https://doi.org/10.1080/01431161.2016.1275059

[69] Safonova, A. et al., 'Detection of fir trees (*Abies sibirica*) damaged by the bark beetle in unmanned aerial vehicle images with deep learning', *Remote Sens.*, vol. 11, no. 6, 2019, p. 643. https://doi.org/10.3390/rs11060643

[70] Hellmann, C. et al.,' Heterogeneous environments shape invader impacts: integrating environmental, structural and functional effects by isoscapes and remote sensing', *Sci. Rep.*, vol. 7, no. 4118, 2017. https://doi.org/10.1038/s41598-017-04480-4

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[72] Mulla, D. J., 'Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps', *Biosyst. Eng.,* vol. 114, 2013, pp. 358–371. https://doi.org/10.1016/j.biosystemseng.2012.08.009

[73] Leitão, P. J., & Santos, M. J. 'Improving models of species ecological niches: a remote sensing overview', *Front. Ecol. Evol.*, vol. 7, no. 9, 2019. https://doi.org/10.3389/fevo.2019.00009

[74] Ricciardi, A. et al., 'Invasion Science: a horizon scan of emerging challenges and opportunities', *Trends Ecol. Evol*., vol. 32, no. 6, 2017, pp. 464–474. https://doi.org/10.1016/j.tree.2017.03.007

[75] Mulla, D. J, 2013.

[76] Mulder, V. et al., 'The use of remote sensing in soil and terrain mapping: A review', *Geoderma,* vol. 162, no. 1-2, 2011, pp. 1–19. https://doi.org/10.1016/j.geoderma.2010.12.018

[77] Cassidy, E., 'High-resolution sea surface temperature data available in the Cloud', *EARTHDATA-NASA* [website], 13 February 2020, https://earthdata.nasa.gov/learn/articles/tools-and-technology-articles/mur-sst-in-the-cloud (accessed 15/08/2020).

accessible, comprehensive, high-resolution (3 and 9 km) soil moisture data.[78] *Digital Earth Australia* (DEA) is a platform that uses spatial data and images recorded by satellites orbiting our planet to detect physical changes across Australia in unprecedented detail.[79] DEA products provide information about ground cover, crop health, water, and coastal environments, which are vital to maintain biosecurity.

SpaceX is launching *Starlink*, a network of low Earth orbit (LEO) satellites, that will ultimately create a global communications system capable of high-speed broadband internet connections endeavouring for global coverage by 2021.[80] Satellite imagery has the potential for modelling past, present, and future populations of large-sized wild animals, potentially including camels and buffalo in the Australian rangelands. Satellite surveys require little regulation or logistical effort, are safe and do not disturb the target animals. The potential for collecting unprecedented amounts of data on wild animal population distributions, abundances, behaviours, and habitat use will increase with increasing satellite coverage.[81]

Many types of miniature sensors have now been developed and includes examples such as accelerometers, gyroscopes, magnetometers, micro cameras, and barometers. Together, these devices make it possible to efficiently track animal movements with unparalleled precision. The 'physiological cost' of behaviours can also be efficiently measured – that is, whether an animal is trying particularly hard to reach a destination, or within a particular location, to capture its prey.[82]

3.3 GENETIC DETECTION AND PLATFORMS

Interest in the application of advanced genetic technologies, such as gene editing and RNAi, is growing rapidly across disciplines, jurisdictions and for parties affected by the impact of invasive species. Genomics is becoming part of the invasive species management toolbox by providing accurate diagnostics, identification of sources and pathways, and foundational knowledge on which to base risk assessments (See Genomics surveillance in Section 3.1). Since its emergence as a reliable tool for conservation and invasion biology,[83] the number of eDNA studies published has exponentially increased, and many government agencies have established eDNA-based monitoring programs[84].

Several tools, such as real-time quantitative polymerase chain reaction (qPCR), DNA barcoding, lateral flow device (LFD), and Loop-mediated isothermal amplification (LAMP) test kits, are now available for rapid identification.[85] Both LAMP and qPCR methods are considered superior to other available molecular diagnostic techniques and are very similar in terms of sensitivity and specificity.[86,87] Most importantly, advancements in LAMP and qPCR-based technologies have made

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78 Cassidy, E., 'Sensing invasive species from space', *EARTHDATA-NASA* [website], 22 May 2020, https://earthdata.nasa.gov/learn/articles/sensing-invasive-species (accessed 15/08/2020).

79 Geoscience Australia, 'About', *Digital Earth Australia–Australian Government* [website], n.d., https://www.ga.gov.au/dea/about (accessed 02/10/2020).

80 Gill, D., 'Outside looking in: Satellites in the climate crisis', *EARTH.ORG* [website], 24 March 2020, https://earth.org/outside-looking-in-satellites-in-the-climate-crisis/ (accessed 15/08/2020).

81 Wang, D., Shao, Q. & Yue, H., 'Surveying wild animals from satellites, manned aircraft and unmanned aerial systems (UASs): A review', *Remote Sense.*, vol. 11, no. 11, 2019, 1308. https://doi.org/10.3390/rs11111308

82 Ritchie, E. & Blake, A., 'From drone swarms to tree batteries, new tech is revolutionising ecology and conservation', *The Conversation* [website], 9 May 2018, https://theconversation.com/from-drone-swarms-to-tree-batteries-new-tech-is-revolutionising-ecology-and-conservation-94920 (accessed 15/08/2020).

83 Goldberg, C. S., Strickler, K. M. & Pilliod, D. S., 'Moving environmental DNA methods from concept to practice for monitoring aquatic macroorganisms', *Biol. Conserv.*, vol. 183, 2015, pp. 1–3. https://doi.org/10.1016/j.biocon.2014.11.040

84 Seymour, M., 'Rapid progression and future of environmental DNA research', *Commun. Biol.*, vol. 2, no. 80, 2019. https://doi.org/10.1038/s42003-019-0330-9

85 Mumford, R. A., Macarthur, R. & Boonham, N., 'The role and challenges of new diagnostic technology in plant biosecurity', *Food Sec.*, vol. 8, no. 1, 2016, pp. 103–109. https://doi.org/10.1007/s12571-015-0533-y

86 Khan, M. et al., 'Comparative evaluation of the LAMP assay and PCR-based assays for the rapid detection of *Alternaria solani*', *Frontiers in Microbiology*, vol. *9*, 2018, 2089. https://doi.org/10.3389/fmicb.2018.02089

87 Durand, L. et al., 'Comparative evaluation of loop-mediated isothermal amplification (LAMP) vs qPCR for detection of Toxoplasma gondii oocysts DNA in mussels', *Experimental Parasitology*, vol. 208, 2020,107809. https://doi.org/10.1016/j.exppara.2019.107809

these methods suitable to field applications outside laboratory settings, where there is availability of battery-powered portable platforms such as the LAMP-based *Genie*® II (Optigene, UK)[88] or the qPCR-based *Franklin*™ Thermocycler (Biomeme (USA)[89]; the latter allowing inspectors to identify pests and pathogens directly in the field or high-risk sites in under 40 minutes with little training.
In comparison, LAMP assays require less consumables and less time to process raw samples for analysis than qPCR, but require a greater input of DNA to achieve reliable detections, wherein qPCR assays can reliably amplify as little as two DNA copies/µL for detection.[90] This makes qPCR a superior technology to detect environmental DNA (eDNA), which is the DNA of organisms secreted into the environment via faeces, mucus, and gametes (an organism's reproductive cells), as well as through shed cells, skin, hair, and decomposing carcasses. It is readily detectable in soil and water samples and can bypass many of the issues inherent in observing or capturing an organism.
The main disadvantages to both techniques are the costs of molecular consumables and the need for high quality primers that are specific to the species of interest and which must be developed *a priori*.

The University of Canberra is now evaluating the Biomeme *Franklin* platform for a pre-border use case involving ornamental fish.[91,92,93] This includes the detection of pathogens and parasites in the live ornamental fish trade using environmental DNA (eDNA) techniques, which has the potential to greatly improve current biosecurity practices.[94]

Environmental DNA (eDNA) has also become an effective approach for the early detection of *Didymosphenia geminate* in the United States,[95] and as it is a national priority exotic environmental biosecurity pest, has also potential in Australia to be used for detection of vertebrate pests.

The specificity and broad contextual application of eDNA makes the approach attractive as an invasive species detection tool.[96,97] It should be noted that first-order estimates of eDNA decay rates vary considerably, from a half-life 0.7 h in a multi-species assay to 71.1 h in Antarctic icefish.[98]
eDNA is currently touted as being highly effective although meta-barcoding needs more efficiency. For eDNA metabarcoding to truly take off, current assessments of ecological quality would need to be adapted to the eDNA metabarcoding framework. These changes must be feasible on a large scale, particularly when considering thresholds between countries and the differences between traditional and molecular methods. To calibrate, molecular methods would need to be applied simultaneously with existing systems in key environmental gradients which would likely be accomplished during development and testing of molecular methods. The potential of eDNA metabarcoding in biological research seems almost limitless, but the technique requires scientific collaboration and coordination.[99]

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[88] Ge, B. et al., 'Multi-laboratory validation of a loop mediated isothermal amplification method for screening *Salmonella* in animal food', *Frontiers in Microbiology*, vol. 10, 2019, 562. https://doi.org/10.3389/fmicb.2019.00562

[89] Rahimi, F. et al., 'A review of portable high-performance liquid chromatography: The future of the field?', *Chromatographia*, vol. 83, no. 10, 2020. pp. 1165–1195. https://doi.org/10.1007/s10337-020-03944-6

[90] Trujillo-González, A. et al., 'Can environmental DNA be used for aquatic biosecurity in the aquarium fish trade?', *Biological Invasions*, vol. 22, no. 3, 2019, pp. 1011–1025. https://doi.org/10.1007/s10530-019-02152-0

[91] Thomas, A. C. et al., 'A system for rapid eDNA detection of aquatic invasive species', *Environmental DNA*, vol. 2, no. 3, 2020, pp. 261-270. https://doi.org/10.1002/edn3.25

[92] CISS, 'Research', *CISS* [website], 2017, https://invasives.com.au/research/biosecurity-edna/ (accessed 02/10/2020).

[93] CISS, 'Researchers test their real time eDNA detection kits in Thailand', *CISS* [website], 15 April 2020, https://invasives.com.au/news-events/researchers-test-real-time-edna-detection-tests-thailand/ (accessed 02/10/2020).

[94] Trujillo-González, A. et al., 'Parasite detection in the ornamental fish trade using environmental DNA', *Sci. Rep.*, vol. 9, no. 5173, 2019. https://doi.org/10.1038/s41598-019-41517-2

[95] Keller, S.R. et al., 'Environmental DNA genetic monitoring of the nuisance freshwater diatom, *Didymosphenia geminata*, in eastern North American streams', *Diversity & Distrib*., vol. 23, no. 4, 2017, pp. 381–393. https://doi.org/10.1111/ddi.12536

[96] Hinlo, R. et al., 'Performance of eDNA assays to detect and qualify an elusive benthic fish in upland streams', *Biol. Invasion*, vol. 20, 2018, pp. 3079-3093. https://doi.org/10.1007/s10530-018-1760-x

[97] Kamenova, et al., 'Invasions toolkit: Current methods for tracking the spread and impact of invasive species', *Adv. Ecol. Invasions*, vol. 56, 2017, pp. 1–97. https://doi.org/10.1016/bs.aecr.2016.10.009

[98] Harrison, J. B., Sunday, J. M., & Rogers, S. M. 'Predicting the fate of eDNA in the environment and implications for studying biodiversity', *Proc. Biol. Sci. B.*, vol. 286, no. 1915, 2019. https://doi.org/10.1098/rspb.2019.1409

[99] Ruppert, K. M., Kline, R. J. & Rahman, M. S., 'Past, present, and future perspectives of environmental DNA (eDNA) metabarcoding: A systematic review in methods, monitoring, and applications of global eDNA', *Global Ecology and Conservation*, vol. 17, 2019, e00547. https://doi.org/10.1016/j.gecco.2019.e00547.

Besides these however, one technology in Australia that is currently providing an unprecedented level of data on identifying exotic species and diseases in agricultural settings and also helping to set evidence-based priorities for future research, is the DNA-based tool *PreDicta® B*.[100]

3.4 INTEGRATION INTO FUTURE DIGITAL FARMING

Digital decision technology has the potential to deliver significant productivity benefits to agriculture. Economic modelling has shown that digital agriculture could increase the gross value of Australian agricultural production by $20.3 billion (a 25% increase on 2014-15 levels).[101] A key factor for increased producer use and benefits from digital decision technology in their business is having trust in management of their data, plus confidence in the recommendations digital decision tools provide. If the trust of producers is lost in contributing to data pools (including 'Big Data'), the opportunity and benefits of this technology could easily be lost for a period until that trust is regained.

While there are considerable productivity gains to be made by more efficiently accessing a range of digital data technologies, benefits to producers will be limited in the absence of in-field data communications providing opportunity access data and decisions in real-time.

Historically, most leading producers and agronomists leave the development and integration of the new technologies to innovators and early adopters. Currently many potential digital decision tools are too complex and fragmented to implement, expensive, and often have difficulty in integration of data. There is a need for coordinated assessment across multiple Australian industries to deliver clearly defined recommendations and standards to ensure the future functionality and effectiveness of big data is suited to Australian producers.

Building trust and confidence in the use of digital data is the key pathway for delivery of outcomes for any digital data-based biosecurity investment. There is also a need to provide evidence to producers for changing the existing paradigm of using an analogue process towards digital decision-making through increasing the understanding of the value proposition for the access and use of digital data in decision making for their business. This includes understanding the benefits of enabled real-time access to digital data and associated decision tools in the field.

Identified pathways and cost proven options for the best approach are required for producers to proactively use an evidence-based big data approach to decision making. Successful digital data platforms require broad industry and community stakeholder participation to provide effective function and validation of the tools provided.

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4 SURVEILLANCE TECHNOLOGIES AND SYSTEMS

4.1 GENETIC SURVEILLANCE SYSTEMS

Genetic tools have multiple applications for the active management of invasive vertebrate species. They are reliable, robust and provide vital information (that may not be accessible with non-genetic methods), for the implementation of conservation policies (e.g. early detection using systematic eDNA surveillance and the identification of novel pathogens).

Indirect field signs such as hair and faeces can be subjected to **genetic non-invasive sampling** (gNIS) to confirm species identification.[102] gNIS has the benefit of collecting genetic information without handling animals, which may cause stress. Routine PCR methodologies can be applied as diagnostic tools for identifying species from ambiguous field signs such as hair or faeces. For example, the required species-specific primers are already available to identify foxes as part of the Tasmanian fox eradication program;[103, 104] and to identify Iberian carnivores from faecal DNA, including invasive mammals such as the genet *Genetta*, Egyptian mongoose (*Herpestes ichneumon*) and the North American mink (*Neovison vison*)[105].

PCR detection or identification methods can be used to target short genetic regions (<1000 base pairs). qPCR is marginally more complex but has some benefits over traditional PCR for the identification of species from gNIS. qPCR can amplify shorter DNA regions (<100 base pairs) and is more sensitive to smaller starting amounts of DNA. qPCR has the additional benefit of providing quality control to select optimal DNA samples for further analysis, such as sequencing and genotyping, thus allowing researchers to avoid wasting resources on poor-quality samples that are unlikely to yield results. Physical samples such as faeces or hair are not always required for species detection.[106]

Organisms leave genetic material behind in the surrounding environment (e.g. in water bodies and soil) via excretions and secretions;[107] this is referred to as **environmental DNA** (eDNA). Single-species detection from eDNA is possible using PCR, qPCR or droplet digital PCR (ddPCR). Research on feral pigs (*Sus scrofa*) in North America has demonstrated the efficiency of a species-specific qPCR approach on samples from various water bodies in detecting terrestrial species.[108] In Australia, species-specific eDNA assays have been developed to detect redfin perch (*Perca fluviatilis*) – an invasive freshwater fish,[109] and the invasive European carp (*Cyprinus carpio*), in two lakes in Tasmania[110]. This highlights that eDNA assays have implications for providing early detection of

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103 Ramsey, D. S. L. et al., 'An examination of the accuracy of a sequential PCR and sequencing test used to detect the incursion of an invasive species: The case of the red fox in Tasmania', *J. Appl. Eco*l., vol. 52, no. 3, 2015, pp. 562–570. https://doi.org/10.1111/1365-2664.12407

104 Ramsey, D. S. L. et al., 'Detecting rare carnivores using scats: Implications for monitoring a fox incursion into Tasmania', *Ecol. Evol*., vol. 8, no. 1, 2018, pp. 732–743. https://doi.org/10.1002/ece3.3694

105 Fernandes, C. A. et al., 'Species-specific mitochondrial DNA markers for identification of non-invasive samples from sympatric carnivores in the Iberian Peninsula', *Conservation Genetics*, vol. 9, 2008, pp. 681–690. https://doi.org/10.1007/s10592-007-9364-5

106 Kierepka, E. M. et al., 'Identification of robust microsatellite markers for wild pig fecal DNA', *Journal of Wildlife Management*, vol. 80, 2016, pp. 1120–1128.

107 Harper, L. R. et al., 'Environmental DNA (eDNA) metabarcoding of pond water as a tool to survey conservation and management priority mammals', *Biological Conservation*, vol. 238, 2019, 108225. https://doi.org/10.1016/j.biocon.2019.108225

108 Williams, K. E. et al., 'Detection and persistence of environmental DNA from an invasive, terrestrial mammal', *Ecology and Evolution*, vol. 8, no. 1, 2018, pp. 688–695. https://dx.doi.org/10.1002%2Fece3.3698

109 Furlan, E. M. & Gleeson, D., 'Environmental DNA detection of redfin perch, *Perca fluviatilis*', *Conservation Genet. Resour*., vol. 8, 2016, pp. 115–118. https://doi.org/10.1007/s12686-016-0523-1

110 Furlan, E. M. et al., 'eDNA surveys to detect species at very low densities: A case study of European carp eradication in Tasmania, Australia', *J. Appl. Ecol*., vol. 56, no. 11, 2019, pp. 2505–2517. https://doi.org/10.1111/1365-2664.13485

invasive species, which may initially be present in low numbers. Single-species detection methods are relatively cheap, fast, and robust, but require prior knowledge of the target species to design appropriate detection methods. If prior knowledge of the target species is unavailable, species can be identified from gNIS using Sanger sequencing to generate a DNA barcode.[111]

Next-generation sequencing can facilitate the simultaneous identification of entire communities (i.e. multiple species). **DNA metabarcoding** from environmental samples has the potential to be used as an early warning system for the detection of invasive non-native species, can be used for continuous monitoring programmes, and has been extensively applied for tracking biological invasions in aquatic ecosystems.[112] **eDNA metabarcoding** studies targeting mammalian communities are relatively rare in comparison with other taxonomic groups,[113] but this may change now that there are established metabarcoding protocols for detecting and monitoring whole communities using vertebrate[114] or mammal-specific primer sets[115]. eDNA metabarcoding is an emerging technique for invasive mammal detection and monitoring, and there are important considerations for its use. Due to the high sensitivity of metabarcoding, contamination is a concern.[116] It is therefore essential that specialised eDNA laboratory facilities (akin to working with ancient DNA) are used.[117] **Single nucleotide polymorphisms** (SNPs) have been termed critical for studies on ecology and conservation biology and includes topics such as local adaptation, population structure, and individual identification.[118] The recent advancements of SNP genotyping techniques have presented an exciting opportunity for developing simple inexpensive methods to differentiate between native and non-native conspecifics, regardless of their genetic similarity.[119]

4.2 BIOSENSORS

Recent advances in **nanofabrication** have allowed highly sophisticated nano-biosensors with higher degrees of sensitivity to be manufactured cost-effectively and efficiently. With subsequent development, these sensors will play a major role in efficient monitoring of large areas or ports of entry. Furthermore, **nano-biosensors** have been developed to detect pathogens (fungal, viral and bacterial) in crops and animals[120,121,122] and they hold the potential to be also developed for invasive

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vertebrate species. For example, the University of Queensland has developed an ultrasensitive gold nanosensor which can detect microRNA with 100 aM detection limit in the spiked sample.[123]

Nanosensors have the ability to function as precision chemical sensors and if networked and scaled accordingly, have the potential to signal the presence of invasive species.[124] One ‘natural nanosensor’ that has proven highly effective over the past two decades in invasive species management is the use of **detector dogs**. Initially used to detect the scat and other signs of cryptic endangered species,[125] detector dogs have been successfully demonstrated to detect bird carcasses resulting from impacts with anthropogenic structures,[126] identifying animal parts in illegal wildlife trafficking,[127] and uncovering of invasive species[128]. Dogs have also been used to rapidly detect the signs of small to large invasive mammals, including rabbits on Macquarie Island,[129] feral cats,[130] nutria,[131] and mongooses[132]. Detector dogs were integral to the Tasmania fox eradication program, where they were used to detect scats, which were then genetically tested to detect fox presence as discussed earlier.[133] However, detector dogs have also effectively discovered a variety of other invasive taxa, including Dreissenid mussels,[134] brown tree snakes and Burmese pythons,[135] insects,[136] and invasive weeds[137] (including in eradication programs[138]). Detector dogs are also commonly used to examine both outgoing and incoming cargo at ports by detecting volatile organic compounds (VOCs) released by invasive plants, insects, and pathogens, over a large area.[139]

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Interestingly, recent studies suggest that honeybees can also be trained for the identification of different odorants. Utilising the behavioural characteristics, honeybees are now being studied to understand how to build better natural biosensors.[140] Sniffer bee technology has been employed in various applications, which includes identification of explosives, various chemicals of diverse molecular structure, odorants emitted from flowers/plants, detection of food contamination and also successful identification of biomarkers in the field of medicine.[141] E-nose devices, such as Sensigent's *Cyranose* e-nose, are basically engineered biomimics of a dog's nose, and are currently used to detect the presence of hazardous microbes on crops, plant diseases, and wood rot caused by pathogenic fungi.[142,143,144] Portable e-nose devices built with low-cost sensor components and micro-controllers could be readily deployed in the field (e.g. attached to drones, or at a port of entry) to detect VOCs,[145] including those emitted by plants when vegetative tissues are damaged by invasive species[146].

4.3 ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Machine learning and vision, combined with artificial intelligence, can help validate species observations and establish comprehensive intelligent decision support systems.[147,148] Data collected from sensors, drones, citizen scientists, and satellites, with machine learning algorithms for near-real-time on-board data analysis for detection and verification of invasive species, has the ability to transform management of invasive species. **Machine vision techniques** already have been successfully developed to computerise genus or species identification for various animals.
For example, the U.S. Geological Survey (USGS) is collaborating with Conservation Metrics Inc. in Guam to create machine vision algorithms from existing camera trap images to monitor the invasive brown tree snake (*Boiga irregularis*), where it is known to negatively impact the islands' native bird fauna.[149]

In Australia, a recently designed machine learning innovative software tool, *ClassifyMe,* provides users with the opportunity to utilise state-of-the-art image recognition algorithms without the need for specialised computer programming skills.[150] *ClassifyMe* is especially designed for field researchers, allowing users to sweep through camera trap imagery using field computers instead of office-based high-speed processor computers.

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142 Wilson, A. D., 'Diverse applications of electronic-nose technologies in agriculture and forestry', *Sensors,* vol. 13, no. 2, 2013, pp. 2295–2348. https://doi.org/10.3390/s130202295

143 Baietto, M. et al., 'The use of gas-sensor arrays in the detection of bole and root decays in living trees: Development of a new non-invasive method of sampling and analysis', *Sensors & Transducers*, vol. 193, no. 10, 2015, pp. 154–160. https://www.sensorsportal.com/HTML/DIGEST/october_2015/Vol_193/P_2748.pdf (accessed 02/10/2020).

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Computing capabilities have developed to the point that systems processing real-time video data are now feasible. **Machine vision technology** requires no physical contact with an animal yet could identify animals to species (or group of species) level. If this ability is linked to an **automated gate** then the opportunity to manage a limiting resource, such as surface water, delivers infinitely more options. Unwanted pests could be excluded while domestic stock could receive uninhibited access. Alternatively, some pests could be trapped while others are excluded. The precise setup could be tailored to suit specific circumstances, all using the same infrastructure of an automated gate controlled by machine vision software.[151] CISS is currently developing next generation automation technologies for pest animal control (Intellitraps) which use **computer vision** and **machine learning algorithms** coupled with **artificial intelligence**.[152]

The application of thermal sensors to ecological and wildlife monitoring purposes has also been keenly investigated by researchers over the years.[153,154,155,156,157] Thermal sensors have the potential to address common issues associated with traditional survey techniques, such as visual acuity and observer fatigue, especially when attempting to detect cryptic targets or surveying large areas.[158] Automated computer software systems for detecting and identifying target objects from thermal imagery, combined with artificial intelligence and machine learning, have the potential to quickly and accurately analyse large imagery datasets.[159]

Technological advancements are facilitating **acoustic detection** of organisms that were previously far less audible to the human ear.[160] For example, acoustic sensors (piezoelectric sensors, lasers, Doppler vibrometers, ultrasound microphones) are currently being used to monitor rodents and insect pests in grain shipments.[161] Acoustic sensors are also being demonstrated to detect the presence of mosquitoes. For example, a newly developed program called *HumBug* is designed to collect audio recordings of mosquitoes and subsequently prime machine learning algorithms to identify the 3,600 known species of mosquitoes based solely on sound. The aim is to build a sophisticated program that will inform users (e.g. via smartphones, wearable technologies) about the occurrence of mosquito species in a user's vicinity. Alerts such as these ideally could be integrated into national biosecurity programs enabling fast detection of invasive mosquitoes and/or invasive pathogens (e.g. Zika virus) spread by mosquito vectors.[162]

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Examples can also be found for vertebrates including development of acoustic detection technology for the Asian house gecko as part of the Gorgon project.[163] CISS is investing in the development of a cost-effective remote acoustic surveillance, detection and reporting solution, using Western Australia's starling control program as an initial case-study.[164, 165]

4.4 ROBOTICS AND UNMANNED AERIAL VEHICLES (UAVS)

As we witness the advances in sensors, robotics, drones and AI, there is a distinct possibility that responding to invasive species across difficult terrains will be highly automated which will further lead to minimising human effort.[166] For example, **robots** can provide added capacity in adverse conditions for humans, such as underwater, in extreme weather events, or at times of low visibility.

Drones (UAVs and underwater **remotely operated vehicles** [ROVs]) can efficiently and economically cover a large geographic range, reach uncharted areas, cover significant territory and topography, carry an array of cameras and sophisticated sensors, and efficiently collect biological specimens, or accurately target and eliminate individual organisms.[167] **Multispectral** and **hyperspectral sensors** attached to UAVs can be flown over most terrain to assess the health of the vegetation below.[168] Drones can potentially replace aircraft in carrying enhanced sensor packages, for instance LIDAR[169], and are also touted to be adopted for invasive rodent eradication programs.[170]

Australian company, Ninox Robotics, is developing high-tech surveillance by utilising UAVs with advanced real-time thermal imaging capabilities to detect invasive pests, including wild dogs, pigs or rabbits, across difficult terrains. Trials for Ninox's *SpyLight System*, the most ambitious for civilian drones ever conducted in Australian airspace, concluded that using long-range UAVs had the potential to detect large animals (in this case, kangaroos) at landscape-scale but their detection and identification technology needed to be improved before it matched or surpassed the accuracy of conventional aerial survey methods.[171]

Research is continuing on the use of drones for pest monitoring and management with several Australian agricultural consultancy companies offering drone services for crop and soil monitoring. Additionally, state and federal agricultural agencies are also increasingly focusing on the use of drones for crop, disease and pest monitoring.[172]

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Insect-inspired **miniaturisation,** which involves working in synergy with the natural world rather than trying to copy it, is a ground-breaking project being developed by the Massachusetts-based Charles Stark Draper Laboratory (USA). The group's *DragonflEye* project is developing an insect-controlled backpack – with integrated energy, guidance and navigation systems – that effectively turns dragonfly insects into 'cyborg drones'. The tiny backpack, fitted with a solar panel and combined with optogenetics, essentially stimulates the 16 specific neurons that correspond to flight in dragonflies. The *DragonflEye* can consume biomatter from its environment to store and recharge energy in its body thus functioning as a '**bio-battery**' and can play an important role in invasive species monitoring over a longer duration.[173]

4.5 DIGITAL COMMUNICATIONS

The **smartphone-enabling technologies,** such as built-in sensors, Bluetooth, radio-frequency identification (RFID) tracking, and nearfield communications (NFC), allow it to be an integral part of IoT and also the most likely device to be used in identifying or locating invasive species.[174,175] Smartphones possess several wireless data transfer modalities (e.g. cellular data service, Wi-Fi, Bluetooth), allowing test results to be displayed immediately to the user and/or transmitted to cloud databases. Nevertheless, smartphones cannot function alone as laboratory instruments. Rather, they need to be augmented by other accessories. Such augmented devices have great potential as mobile diagnostic platforms for analysis of invasive biologicals. In recent years, many external sensor modules have been designed and integrated with smartphones to extend their capabilities for extracting more-sophisticated diagnostic information. These portable, low-cost devices have the potential to run routine tests, which are currently performed by trained personnel using laboratory instrumentation, rapidly and on-site, due to the global widespread use of smartphones.[176]

Many new companies are also offering sensors based on the emergent and promising technique of **NIR spectroscopy**. Consumer Physics has introduced the in-house-developed, world's first smartphone with the built-in molecular sensor, *SCiO*, that can scan diverse arrays of materials including food and could play a key role in invasive species detection.[177]

Mobile phone and iPad users can now access the latest information about Australia's vertebrate pest animals via the new *Field Guide to Pest Animals App*. Developed by the former Invasive Animals CRC (now CISS), this app contains species' profiles for Australia's worst pest animals, including species' descriptions, photo galleries, footprints, audio calls, maps, control techniques, and quick links to other pest control resources.[178] In addition to the Australian *FeralScan App* (See Section 7.1.1), various groups across the United States have also invested in the development of smartphone apps to make reporting data on invasive species easier than ever.[179]

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4.6 ROLE OF COMMUNITIES

The use of reports from the community of their encounters with invasive species is encompassed by the term 'passive surveillance'.[180] Recognition of the usefulness of **community surveillance** for detecting new incursions, or new foci of incursions, has resulted in pest and disease management programs routinely including some level of investment in community engagement activities to encourage reporting. Such activities might include pest displays, newspaper or magazine articles, identification cards, posters, or even rewards. The reporting mechanism is often through a telephone 'hotline' where calls are screened and subsequently directed to the relevant government agency for further action, which might include a site visit to confirm a detection followed by treatment and targeted surveillance by the agency.[181]

Social media may play a critical role to inform detection and transform response strategies to invasive species[182] and researchers have already effectively used online geotagged photo sharing sites, including Flickr and Panoramio, to assist with invasive species management.[183] Incorporating citizen surveillance into the general surveillance framework is indeed an area for further research.[184]

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5 BIOCONTROL SYSTEMS

5.1 CLASSICAL BIOCONTROL

Biological control, or 'biocontrol', is a 'method of reducing or eliminating the impact or damage caused by a target pest or weed using an (introduced) biocontrol agent, traditionally a predator, herbivore, or pathogen'.[185]

There are a number of forms of biological control:

- **Classical biological control**, is where host-specific natural enemies, generally from the native range of the target invasive species, are selected and released into the environment. This form of biocontrol aims to reduce the level of abundance of targeted invasive species so that the environmental impacts are lessened, ideally below measurable damage thresholds.

- **Augmentative biological control**, whereby biocontrol agents are released to achieve a prompt but short-term control of the target at critical times.

- **Conservation biological control**, which mainly centres around managing the environment to increase the populations of naturally-occurring enemies of the invasive pests.

- **Sterile insect technique** which involves release of especially bred sterile males of the same pest species.[186,187,188]

Successful classical biocontrol agents consist of:

- **Micro-organisms and viruses**, such as fungi, particularly rusts for weed targets;[189] and viruses for vertebrate pest targets (e.g. myxomatosis virus and rabbit haemorrhagic disease virus against European rabbits in Australia)[190].

- **Invertebrates**, such as predators or parasites (e.g. parasitoid wasps against insects).[191,192]

- **Herbivorous arthropods**, (e.g. Cactoblastis moths to control prickly pear).[193]

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Vertebrate pest biocontrol agents are rare, with biocontrol agents under evaluation in Australia for only three vertebrate pest species – rabbits, carp and tilapia.

Long-term strategic programs have been put in place to produce a pipeline of rabbit biocontrol agents through CISS. This includes the national release of a RHDV K5 in 2017, followed by evaluations of a rabbit parasite and RHDV2.[194,195] This has been complemented by an important national rabbit disease monitoring program to measure biocontrol efficacy and to optimise on-going biocontrol releases.

5.2 EMERGING BIOTECHNOLOGIES/SYNTHETIC BIOLOGY

Genetic biocontrol provides opportunities for the control and potential eradication of invasive species. The term 'genetic biocontrol' refers to techniques that alter the genes of an organism to control invasive species in the environment. Some, but not all, of these techniques involve knowledge or manipulation of the genome.[196] It is important to note that genetic biocontrol is not a synonym for the use of genetically engineered organisms. Existing technologies that use naturally occurring genetic alleles, irradiated organisms, chromosomal segregation techniques, or endoparasitic bacteria (i.e. *Wolbachia*), constitute genetic biocontrol techniques that would not be considered genetic engineering.[197]

Genetic biocontrol options emerging for invasive species control, typically consist of:

- **Sterile release**: A technique that involves sterilisation and release of males into wild populations of the same species can be useful in the control of invasive or pest species.[198]

- **YY Males**: The YY male tilapia technology involves the genetic manipulation of sex. Feminisation and progeny testing is undertaken to identify the novel YY genotype that sires only XY natural male progeny or natural male tilapia.[199]

- **Trojan Female Technique**: The 'Trojan Female Technique' is where females pass on genes that make male offspring infertile.[200] Proof of utility has also been achieved in mice by screening the sperm parameters of numerous genetic strains of mice, each of which shares a common set of nuclear DNA but a different mitochondrial DNA sequence, consisting of a unique set of variants. This research has verified that variants within the mitochondrial genes of mice also affect male fertility.

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- **RNAi**: A biological process that involves RNA molecules inhibiting gene expression or translation by neutralising targeted messenger RNA molecules through an increase or decrease in their activity.[201] In the wild, this method may protect species against viruses that insert parasitic nucleotide sequences and 'may also be applicable for invasive species as a highly precise (taxa specific), efficient, and stable biopesticide, using prey species as vectors for transmission'.[202]

Recently, there has been great excitement around the possibility of using synthetic gene drives as a tool for pest control in general,[203,204] and for biodiversity conservation in particular.[205] **Gene drives** are genetic elements that manipulate reproductive processes to gain a transmission advantage over the rest of the genome. This often occurs through the distortion of meiosis or gamete development (termed 'meiotic drive'), or by breakage and self-insertion into the homologous target sequence (termed 'homing-based drive').[206]

Gene drives may pose considerable risks because, once introduced, they intentionally drive through populations with no further human control unless genetic safeguards are built into the drive. Other risks may include possible gene transfer between modified individuals and endemic species, strong public scrutiny, and unforeseen ecosystem effects following successful eradication.[207]

Research is progressing to demonstrate proof of concept of this platform technology in a mouse model.[208,209] If successful, this transformational technology could potentially be applied to a number of vertebrate pests, such as rabbits and feral cats.[210,211] Other potential target pests include cane toads.[212]

Although scientific and regulatory hurdles exist for the practical use of genetic biocontrol to control invasive species, a major hurdle that also needs to be overcome will be public acceptance of the technology. Gaining public trust will also be an essential component in the development of new genetic biocontrol methods and will be a major barrier to implementation of any genetic biocontrol.[213]

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6 INTEGRATED LANDSCAPE MANAGEMENT

6.1 LANDSCAPE LEVEL TECHNOLOGY INTEGRATION AND SYSTEMS

The control and eradication of invasive species is a landscape-scale problem, often making local management strategies inadequate for the control or eradication of established invasive species. Historically, the control of terrestrial invasive species has been largely based on general population reduction by trapping, shooting or poisoning (e.g. 1080 baiting discussed further in Section 6.4) in focal areas of the landscape.[214] Even though active population reduction has been effective at decreasing vertebrate pest populations, its effectiveness is very much dependent on the life-history traits of the focal species.[215]

Landscape-scale approaches to wildlife management have long been adopted in marine and terrestrial conservation biology,[216,217] motivated by the loss of wildlife populations in degraded and fragmented landscapes and seascapes.[218] Landscape-scale control has been actively promoted as best practice management for a number of established invasive species; however, these management actions have often failed to consider the distribution and connectivity of local populations across the landscape. This is despite modelling frameworks now being available to forecast the spread of invasive species in spatial settings, which explicitly account for metapopulation structure.[219,220,221]

New technologies, such as drones (discussed above) and nanosatellites, ensure surveillance, detection, and identification of an invasive species, on a landscape-scale as it spreads and expands its range, especially in uncharted areas.[222] Managing landscape-scale environmental problems, such as biological invasions, can also be facilitated by integrating realistic geospatial models with user-friendly interfaces that stakeholders can use to make critical management decisions.[223]
The technologies described later in this section, if scaled, offer the prospect to better detect and monitor invasive species over sizable geographic ranges.

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6.2 DIGITAL TECHNOLOGIES (INTERNET OF THINGS)

The ability to implement wireless sensor networks, often in remote terrains, has increased the ability to monitor not only invasive species but to also better assess species that are endangered and gather information about their natural environment to ensure better protection. **IoT networks** are providing cost effective solutions to track and monitor wildlife. New advantages including improved battery life, improved sensor capabilities and real-time data analysis, are all being used in IoT deployments.[224] Because of the connected ecosystem developed by evolving smartphones, citizen scientists are also playing a critical role in early detection of invasive species.[225]

Previously, the Internet of Things (IoT) was normally based around the use of internet-connected sensors (visual, chemical, acoustic, and biological) to make decisions or increase productivity within our homes and cities. However, the adaptation of IoT based on near real-time data collection integrated into environmental protection is now being explored globally.[226,227] Readily available **low-cost sensor components** and **microcontrollers** (e.g. Arduino, Adafruit, and Raspberry Pi) are also continually improving and expanding data collection capabilities.[228] IoT has many technological advantages for ecological research and the monitoring of wild animals. Firstly, IoT can acquire data continuously and also adjust the frequency of data collection through remote adjustment of the sensors, which effectively increases the service time of power supplies. Secondly, IoT can remotely monitor animals and their environment, and thus exclude any effects of human interference to record data more objectively. A network can function for a long period of time and provide interactive services such as reminders and alerts for users by the setting of thresholds on the back-end server by the operator. After installing the management devices, IoT can implement the interaction with the user under the control of the network client and improve the efficiency of animal monitoring and management as shown by the project *Wild Dog Alert*.[229,230] There are also cable free trap-alert systems which successfully use both cellular and satellite networks to transmit messages from desert and coastal locations to trappers in Australia and play a key role in improving the welfare outcomes for captured animals.[231]

6.3 NEW TOOLS: NANOSATELLITES

Small, low-cost **nanosatellite** constellations offer an alternative method to drones and satellites for collecting remote-sensing data.[232] Traditional earth observation satellites, such as Landsat 8, cost approximately $900 million and require decades-long development time. This is in contrast to nanosatellite constellations which can leverage the low cost of the satellites and low launch costs coupled with a rapid launch cycle. However, nanosatellites are not without challenges. Sensors for

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230 Meek, P. D. et al., 'Camera trapping technology and advances: Into the new millennium', *Aust. Zool*., vol. 40, no. 3, 2020. https://doi.org/10.7882/AZ.2019.035

231 Meek, P. D. et al., 'Satellite and telecommunication alert system for foot-hold trapping', *Wildlife Research*, WR20043, 2020, https://doi.org/10.1071/WR20043

232 Selva, D. & Krejci, D., 'A survey and assessment of the capabilities of Cubesats for Earth observation', *Acta Astronaut*, vol. 74, 2012, pp. 50–68. https://doi.org/10.1016/j.actaastro.2011.12.014

nanosatellite platforms must generally be smaller and operate with reduced power, and there are data analysis and integration challenges.[233] Even given these limitations, the potential of implementing nanosatellites for landscape-scale monitoring for detecting significant population changes of invasive species across very large regions is highly significant.[234]

6.4 OPTIMISATION OF CURRENT BEST PRACTICE TECHNOLOGIES

Control programs need to be continually tailored to suit the landscape. For example, in NSW pig control in the western region includes aerial shooting followed up with ground baiting and trapping, whereas in the eastern region it usually involves ground baiting and trapping.[235] It is well established that 'coordinating invasive species control in an area with multiple human activities and domestic companion animals remains challenging; the high number of individual land managers makes landscape-scale activities harder to coordinate; and the ongoing movement of people and goods makes biosecurity more challenging. Hence, effective community engagement is essential to the success of any program'.[236]

Current vertebrate pest landscape-scale management strategies are based on:

1. Large-scale aerial baiting (currently 1080 based)
2. Exclusion and cluster fencing
3. Self-disseminating biocontrol agents.

Over the next decade, opportunities exist to develop technologies to improve the efficiency and effectiveness of large-scale aerial baiting and exclusion fencing. For fencing, this includes eradication decision support tools to optimise eradication of target pest animals within clusters or exclusion fences. In Central and Central-Western Queensland, the primary target species for exclusion are dingoes and kangaroos, as well as secondary target species including feral pigs, feral goats and foxes, that are considered pests to agriculture. The lethal control of these species is widespread within cluster fences, which by 2019 encompassed ~66,000 km^2 of protected livestock grazing land in Central-Western Queensland alone.[237] Another aspect of landscape-scale management strategy is improved control tools that target specific delivery systems.

6.4.1 Toxins

A naturally occurring toxin,1080, found in over 30 Australian plant species, is also used as a vertebrate pesticide for baiting pest animals. Toxin 1080 offers a degree of target-specificity because it is particularly lethal to placental carnivores, such as foxes and wild dogs, while carnivorous marsupials, birds and reptiles, have a much higher tolerance to the pesticide.[238] The widespread use of successive 1080 baiting, particularly in Australia and New Zealand, has meant that populations of

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[233] Dash, J. & Ogutu, B. O., 'Recent advances in space-borne optical remote sensing systems for monitoring global terrestrial ecosystems', *Prog. Phys. Geogr.*, vol. 40, 2016, pp. 322–351. https://doi.org/10.1177%2F0309133316639403

[234] Still, C., 'Tracking buffaloes and cattle by satellite', *CSIROScope* [website], 27 May 2020, https://blog.csiro.au/tracking-buffalo-satellite/ (accessed 15/08/2020).

[235] Riverina Local Land Services, *Riverina Regional Strategic Pest Animal Plan 2018-2023,* 2018, https://www.lls.nsw.gov.au/__data/assets/pdf_file/0004/820813/Riverina-regional-pest-plan.pdf (accessed 03/10/2020).

[236] Kark, S., Shaw, J. & Possingham, H., 'Project: 4.2.2.1 Optimising feral animal control to benefit threatened species on South East Queensland Islands', *Threatened Species Recovery Hub* [website], n.d., https://www.nespthreatenedspecies.edu.au/projects/optimising-feral-animal-control-to-benefit-threatened-species-on-south-east-queensland-islands (accessed 15/08/2020).

[237] Smith, D., Waddell, K. & Allen, B. L., 'Expansion of vertebrate pest exclusion fencing and its potential benefits for threatened fauna recovery in Australia', *Animals*, vol. 10, no. 9, 2020, p. 1550. https://doi.org/10.3390/ani10091550

[238] National Parks & Wildlife Service (NPWS) - NSW Government, 'National Parks and Wildlife Service aerial baiting program 2020', *NPWS NSW* [website], 20 May 2020, https://www.environment.nsw.gov.au/topics/animals-and-plants/pest-animals-and-weeds/managing-pest-animals-and-weeds/national-parks-and-wildlife-sevice-aerial-baiting-program-2020 (accessed 15/08/2020).

target species have been repeatedly exposed to the toxin, increasing the risk for developing bait-resistance through either bait avoidance or toxin-tolerance. Bait-resistance highlights the need for proactive management operations to minimise conditions that contribute to development of bait-resistance.

A complement to 1080, **Para-aminopropiophenone** (PAPP), the first new predator toxin in 50 years, was recently developed for the broad-scale management of wild dogs and foxes,[239] feral cats,[240] and stoats in New Zealand[241]. When ingested, PAPP converts normal haemoglobin in red blood cells to methaemoglobin, which is unable to carry oxygen to the heart and brain. This leads to lethargy, unresponsiveness and death.[242]

In Australia, HOGGONE® micro-encapsulated is a new sodium nitrite feral pig bait that has the same mode of action. Pigs are more susceptible because they lack the protective enzymes present in other species.[243]

Alternative delivery mechanisms for toxins, delivering lethal doses that would reduce opportunity for learned aversion, still require further investigation, particularly in the field. Spring-loaded mechanical ejectors (known as M-44 ejectors or canid pest ejectors) were registered for use in Australia in 2016. The device is triggered by a minimum force required to release the toxin, i.e. by an animal pulling on the trigger with its teeth.[244] Feral cat grooming traps (e.g. *Spitfire,*[245] *Felixer*[246]) use a combination of criteria based around body size and habits (e.g. scent marking) to trigger a lethal dose of toxin squirted onto the animal's pelt which it then ingests when cleaning itself. Similarly, a range of novel devices have been designed for rats, common brushtail possums and mustelids.[247]

Delivery systems specific to the target species will reduce non-target exposure to toxin that could contribute development of bait-resistance, although such devices may accelerate selection for neophobic individuals in the target species population.[248]

6.4.2 New Tools - Toxins

New, improved, toxicants with humaneness and safety (such as readily available antidotes and increased levels of species specificity) are currently being developed. Building on the platform created by PAPP development, a second red blood cell toxicant, sodium nitrite (SN), [249] also is now commercially available.

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[239] Allen, B. L., 'Para-aminopropiophenone (PAPP) in canid pest ejectors (CPEs) kills wild dogs and European red foxes quickly and humanely', *Environ. Sci. Pollut. Res*., vol. 26, 2019, pp. 14494–14501. https://doi.org/10.1007/s11356-019-04818-7

[240] Johnston, M. et al., 'Efficacy and welfare assessment of an encapsulated para-aminopropiophenone (PAPP) formulation as a bait-delivered toxicant for feral cats (*Felis catus*)', *Wildlife Research*, 2020, WR19171. https://doi.org/10.1071/WR19171

[241] Eason, C. et al., 'Diphacinone with cholecalciferol for controlling possums and ship rats', *N. Z. J. Zool*., vol. 47, no. 2, 2020, pp. 106–120. https://doi.org/10.1080/03014223.2019.1657473

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[243] Animal Control Technologies (Australia) Pty Ltd (ACTA), 'HOGGONE® sodium nitrite feral pig bait', *ACTA* [website], n.d., https://animalcontrol.com.au/products/hoggone (accessed 03/10/2020).

[244] Allen, B.L., 'Para-aminopropiophenone (PAPP) in canid pest ejectors (CPEs) kills wild dogs and European red foxes quickly and humanely', *Environ. Sci. Pollut. Res*., vol. 26, 2019, pp. 14494–14501. https://doi.org/10.1007/s11356-019-04818-7

[245] Eason, C. et al., 'Diphacinone with cholecalciferol for controlling possums and ship rats', *N. Z. J. Zool.,* vol. 47, no. 2, 2020, pp. 106–120. https://doi.org/10.1080/03014223.2019.1657473

[246] Read, J. L. et al., 'Target specificity of the felixer grooming "trap"', *Wildl. Soc. Bull*., vol. 43, 2019, pp. 112–120. https://doi.org/10.1002/wsb.942

[247] Allsop Sinéad, E. et al., 'Reduced efficacy of baiting programs for invasive species: some mechanisms and management implications', *Pac. Conserv. Biol.,* vol. 23, 2017, pp. 240–257. https://doi.org/10.1071/PC17006

[248] Allsop Sinéad, E. et al., 2017.

[249] Blackie, H.M. et al., 'Innovative developments for long-term mammalian pest control', *Pest. Manag. Sci*., vol. 70, 2014, pp. 345-351. https://doi.org/10.1002/ps.3627

Emerging additional options are toxins extracted directly from New Zealand plants as potential new tools.[250] For some plant species (e.g. Tutu *Coriaria arborea*, Karaka *Corynocarpus laevigatus* and Kowhai *Sophora microphylla*), the toxicity to rodents, toxin extraction methods and the chemistry of the toxin, have already been described. Maori community groups and scientists at Lincoln University are currently exploring the potential of natural New Zealand toxins, with a current focus on tutin, the active ingredient in Tutu.[251]

Because of the increased restrictions on rodenticide use, research is expanding on potential new rodenticides. Researchers are investigating new active ingredients as well as rodenticides containing two active ingredients (i.e. an anticoagulant and an acute toxicant in one bait, but at lower concentrations than in single-active-ingredient rodenticides). Some researchers are revisiting formerly registered active ingredients such as norbormide.[252] Some of the research efforts with potential new active ingredients or combinations of active ingredients (e.g. cholecalciferol combined with diphacinone or brodifacoum) have also been reported.[253]

6.4.3 Exclusion and Cluster Fencing

Exclusion and cluster fencing are making eradication or suppression of target pests more efficient and effective, and in the future, application of sensor arrays and application of emerging eradication decision support systems have the potential to better optimise eradication efforts.[254]

Exclusion fencing is being used internationally to protect areas of high conservation value or to create ‘islands’ of protected habitat for native fauna. It has proven a particularly valuable tool in aiding the reintroduction of threatened species to areas from which they have been previously eliminated or displaced by pests. The design of an exclusion fence must be based on the behaviour and physical abilities of the animals it aims to exclude. Many historical exclusion fences were not experimentally tested, were focused on exclusion of single rather than multiple species, and often failed because of faulty design, poor construction, or lack of maintenance.[255]

Substantial investments have been made into constructing pest-proof netting fences (‘cluster fences’) around multiple grazing properties in western Queensland. Effective control of many vertebrate pests is now possible across large areas by denying immigration, which offers widespread and substantial benefits to agriculture and the environment. Similar fences are proposed for more arid areas in southern rangelands of Western Australia.[256] Cluster fences have rapidly been erected in Queensland and now across the rest of Australia, and already there are anecdotal reports of the absence or near-absence of these species. Declines in such pest animals are yielding economic and environmental benefits to livestock producers and could yield benefits for threatened fauna conservation as well.[257]

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[253] Eason, C. et al., ‘Diphacinone with cholecalciferol for controlling possums and ship rats’, *N.Z.J. Zool.*, vol. 47, no. 2, 2020, pp. 106–120. https://doi.org/10.1080/03014223.2019.1657473

[254] CISS, ‘Tools for developing cost-effective decisions for managing invasive pest eradications’*, CISS* [website], February 2019, https://invasives.com.au/research/tools-developing-cost-effective-decisions-managing-invasive-pest-eradications/ (accessed 03/10/2020).

[255] Day, T. I., & Macgibbon, R. ‘Multiple-species exclusion fencing and technology for mainland sites’ in Witmer, G. W., Pitt, W. C. & Fagerstone, K. A., *Managing vertebrate invasive species: Proceedings of an international symposium,* USDA/APHIS Wildlife Services*,* 2007, http://www.aphis.usda.gov/wildlife_damage/nwrc/symposia/invasive_symposium/nwrc_TOC_index.shtml (accessed 03/10/2020).

[256] CISS, ‘Assessment of the biodiversity, economic and productivity gains from exclusion fencing (QLD)’, *CISS* [website], February 2020, https://invasives.com.au/research/assessment-biodiversity-economic-productivity-gains-exclusion-fencing-queensland/ (accessed 3/10/2020).

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7 COMMUNITY ENGAGEMENT

7.1 POTENTIAL OF CITIZEN SCIENCE IN GENERAL SURVEILLANCE

Owing to the huge number of species observations that can be collected by non-professional scientists, 'citizen science' has great potential to contribute to scientific and management knowledge on invasive species. Citizen science has existed for centuries, but the recent adoption of information and communications technology (ICT) in this field (e.g. web or mobile application-based interfaces for citizen training and data generation) has led to a massive surge in popularity, mainly due to reduced geographic barriers to citizen participation. Several challenges exist however, to effectively utilise citizen-generated data for monitoring invasive species (or other species of interest) at the global scale.[258] Despite some data quality issues, the data collected through these citizen science initiatives has been recognised as having great potential to contribute to research due to the number of species observations that can be collected by the public.[259]

Smart mobile platforms powered with greater connectivity, has enabled expansion of the pool of data collectors and analysers. This in turn increases the reach and scale of effectively monitoring invasive species across a diverse geographic range.[260] Citizen scientists can play a crucial role in increasing the on-the-ground capacity for eradication efforts.[261] Volunteer-collected data are now deemed just as accurate as that collected by professionally trained scientists,[262] and there are robust analytical methods to scrutinise big datasets for successful identification of recent trends.[263,264] Current citizen science and crowdsourcing-based programs are designed to report and monitor invasive species by submitting observation data through websites, mobile phone applications, or paper forms.
For example, citizen science biodiversity observations submitted to *iNaturalist,*[265] which collects observations of native and non-native species from people globally, is integrated into the Global Biodiversity Information Facility (GBIF)[266]. GBIF is a web database containing various types of biodiversity data, including citizen and professional scientists' observations of invasive species, and it is now the largest species occurrence database in the world.

7.1.1 Enabling technologies

Using citizen science for the early detection of invasive species has recently become possible at large scales due to the development of collaborative technology, social media and networking, and publicly accessible databases, creating opportunities for anyone to participate in ecological research. Smartphones, equipped with microphones and adequate computational power for acoustic monitoring of invasives such as certain species of birds,[267] are facilitating rapid growth in the population of

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[258] Johnson, B. A., et al., 'Citizen science and invasive alien species: An analysis of citizen science initiatives using information and communications technology (ICT) to collect invasive alien species observations', *Glob. Ecol. Conserv.*, vol. 21, 2020, e00812. https://doi.org/10.1016/j.gecco.2019.e00812

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[263] Kelling, S. et al., 'Taking a 'Big Data' approach to data quality in a citizen science project', *Ambio*, vol. 44, 2015, pp. 601–611. https://doi.org/10.1007/s13280-015-0710-4

[264] Swanson, A. et al., 'A generalized approach for producing, quantifying, and validating citizen science data from wildlife images', *Conserv. Biol.*, vol. 30, 2016, pp. 520–531. https://doi.org/10.1111/cobi.12695

[265] iNaturalist.org, 'How It Works', *iNaturalist* [website], n.d., https://www.inaturalist.org/ (accessed 15/08/2020).

[266] Global Diversity Information Facility (GBIF), 'Free and open access to biodiversity data', *GBIF* [website], n.d., https://www.gbif.org/ (accessed 15/08/2020).

[267] Lane, N. D. et al., 'A survey of mobile phone sensing', *IEEE Commun. Mag.*, vol. 48, 2010, pp. 140–150. https://doi.org/10.1109/ MCOM.2010.5560598

acoustic detectors.[268] Do-it-Yourself (DIY) kite or balloon mapping can also provide low-cost site access and high-resolution sensor transport to support invasive species detection via remote imaging. *Public Lab*[269] uses kite and balloon mapping and also created an open source software *MapKnitter*, to combine aerial images into a georeferenced mosaic.

In Australia, *FeralScan* (www.feralscan.org.au) is a free resource to enable community-led cooperative vertebrate pest management that can be used by anyone to record pest animal activity, evidence of pests, pest damage, and control actions.[270] Data entered into *FeralScan* can be used to help coordinate on ground control to address the problems pest animals are causing in your local and regional area. *FeralScan* currently contains over 213,000 records of pest animals mapped by landholders and communities across Australia.

It can be used to document pest animal activity, communicate the problem to other people, and identify priority areas for pest control. Users can print maps, view and export pest records, and see where other people in their local area are also reporting pest animals.[271] A recent study that analysed the utility of *FeralScan* data collected, concluded that ‘citizen science data can play an important role in managing invasive species by providing missing information on occurrences in regions not surveyed by experts because of logistics or financial constraints’.[272] The platform has also been applied as an integral part of national biocontrol monitoring programs – exemplified by the *FeralScan* Rabbit Biocontrol Tracker role in the national rabbit disease monitoring program.[273]

The Center for Invasive Species and Ecosystem Health at the University of Georgia (USA) harnesses citizen scientists in addressing invasive species. The *Squeal on Pigs* app enables landowners and state officials to report on and work to eradicate feral pig populations; while in Florida, the *IveGot1* app enables users to report real-time sightings of live invasive species, including Burmese python and melaleuca trees.[274] The *IveGot1* app collects the GPS locations of users when they submit images and the images are emailed to local and state verifiers for review.[275]

7.2 COMMUNITY-LED MANAGEMENT

Engaging the interest of community groups in resolving pest or native animal management problems can provide valuable support in achieving coordinated management program objectives. Ideally, there should be broad public and political acceptance of the need for management programs, particularly where native animals or pest animals that are valued by some sectors of the community (e.g. wild horses in Namadgi National Park[276]) are the target species. Strategies to increase awareness and understanding of pest and native animal management issues should aim to inform all these interest groups.

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[270] FeralScan.org.au, ‘Record pest animal activity in your local area to protect farms, biodiversity and communities’, *FeralScan.org.au* [website], 2020, https://www.feralscan.org.au/ (accessed 15/08/2020).

[271] Kontos, E.,’ FeralScan monitoring, mapping program wins award honour’, *South West Voice* [website], 7 December 2016, https://southwestvoice.com.au/feralscan-program-wins-award-honour/ (accessed 15/08/2020).

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[273] Cox, T. E. et al., ‘The impact of RHDV-K5 on rabbit populations in Australia: An evaluation of citizen science surveys to monitor rabbit abundance’, *Sci. Rep*., vol. 9, no. 15229., 2019. https://doi.org/10.1038/s41598-019-51847-w

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[275] Bugwood Apps, ‘Our Applications’, *Bugwood Apps* [website], 2018, https://apps.bugwood.org/ (accessed 15/08/2020).

[276] Olsen, P., *Australia’s pest animals: New solutions to old problems*, Bureau of Resource Sciences & Kangaroo Press Pty Ltd, NSW, 1998.

7.2.1 Best practice adoption/future of learning/knowledge transfer (e.g. webinars etc)

Improving awareness and understanding of pest and native animal management issues facilitates the development and appropriate ownership of management programs and may reduce public opposition that can arise through misunderstanding. Awareness and understanding of pest and native animal management issues could be promoted through:

- web-based information
- provision of information to plant nurseries and pet retailers on notifiable pest animals and the importation of high-risk materials
- media releases
- brochures and signs in parks and reserves
- research programs involving local residents (e.g. opinion polls on animal management)
- meetings and webinars with stakeholders affected by pest and native animal damage (e.g. land managers affected by wild dogs).[277]

The knowledge, skills and management options that underpin pest and native animal management programs need to be maintained through effective education, training and research programs. Australia should develop high-quality tertiary education courses in pest and native animal management, with active collaboration amongst local and regional research groups to resolve knowledge gaps and management problems. Training courses in pest management options, including chemical application and risk management, need to be made available to local operational staff and contractors on a regular basis.[278]

Technological innovation combined with interdisciplinary collaboration is being applied through ideation events, hackathons, and crisis mapping to provide innovative solutions to societal problems.[279,280] For example, in 2017 NASA hosted the *Space Apps* international hackathon which included a challenge to develop a tool to gather information about invasive species in the local neighbourhood over a period of time.[281] Furthermore, crisis mappers have developed new approaches which utilise 'mobile and web-based applications, participatory maps and crowd-sourced event data, aerial and satellite imagery, geospatial platforms, advanced visualization, live simulation, and computational and statistical models'.[282]

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[277] ACT Government, *The ACT Pest Animal Management Strategy 2012–2022*, https://www.environment.act.gov.au/__data/assets/pdf_file/0008/575117/PAMS_WEB.pdf (accessed 15/08/2020).

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8 DISCUSSION AND CONCLUSION

Managing vertebrate pests is a global conservation, biodiversity and biosecurity challenge given their negative economic and social impacts. This report provides an overview of a range of technology and system level opportunities that have the potential to strengthen invasive species management and to develop and deploy integrated biosecurity technology systems. To successfully manage the vertebrate pest species in Australia, it is critical that a *Technology Driven Framework*, using the technological advances identified above, is designed to respond to ongoing threats from vertebrate pests. Any framework should be leveraged to successfully predict any real time biological invasions, allowing early action in the 'invasion curve' and eradication of a pest before its impact becomes too severe.

Despite recent advances, decades old broad-spectrum toxins and traplines are still the mainstay of vertebrate pest control.[283] A technological leap is needed to achieve much more precise, affordable, and socially acceptable vertebrate pest control systems, deployable at great scale across urban, rural, and wilderness landscapes. In practical terms this will involve completing the development and validation of individual technologies; then reaching beyond current approaches and optimising cost-effective procedures for integrating traditional methods (e.g. toxin baiting) with recently developed approaches, such as species-specific toxins, potent lures, real-time monitoring, drones, technologies from completely different fields including AI and IoT, big data handling, and testing at a local scale as a platform for landscape-scale extrapolation.

Emerging technologies that still require significant research and development includes advances in wireless technology for species recognition, the next generation of self-resetting traps, UAVs, and improved species-specific toxin-delivery systems enhanced with advanced lures and new toxins,[284] with selectivity and humaneness[285]. Semiochemical-based lures, when combined with effective delivery technologies, will provide long-life controlled odour release, factors that will help expand the utility of resetting toxin-delivery systems and traps.[286] Ultra-potent lures should expand the range and cost-effectiveness of monitoring devices, resetting toxin-delivery systems, and traps. A long-distance lure is clearly a critical requirement for any minimal-spacing array as the cautious behaviour of pest animals towards artificial devices is also a serious issue requiring integrated research. Sequence-directed inhibition of protein synthesis by RNAi has also tremendous potential. Species-specific by design, RNAi reduces impacts on nontarget species and the environment. Additional research advancing the field of RNAi-based management of vertebrate pest wildlife is timely. Gene drive will also play a vital role moving forward in eradication of vertebrate pests.[287] A recent international review paper concluded that these types of developments offer 'transformational change' in pest control, but this will only be the case if these developments can be integrated into a landscape-scale strategic framework and if more practical field experience is gained.[288]

[283] Hansford, D., *Protecting paradise: 1080 and the fight to save New Zealand's wildlife*, Nelson, New Zealand, Potton and Burton, 2016.

[284] Murphy, E. et al., 'A new toxin delivery device for stoats-results from a pilot field trial', *N. Z. J. Zool.*, vol. 45, no. 3, 2018, pp. 184–191. https://doi.org/10.1080/03014223.2018.1461118

[285] Eason, C. T. et al., 'Trends in the development of mammalian pest control technology in New Zealand', *N. Z. J. Zool.*, vol. 44, no. 4, 2017, pp. 1–38. https://doi.org/10.1080/03014223.2017.1337645

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It is highly imperative to look at vertebrate pest management and identify the '**invasion syndromes**' in the context of Australia, and to understand how technology and a better modelling system concurrently can play a role in aiding the management of vertebrate invasives. Invasion syndrome is a well-established predictive modelling technique that has been recently re-defined as 'a combination of pathways, alien species traits, and characteristics of the recipient ecosystem which collectively result in predictable dynamics and impacts, and that can be managed effectively using specific policy and management actions'. It can be viewed as a systematic approach for predicting biological invasions and facilitating effective management going forward (See Appendix A for an Invasion Syndrome framework and case studies).[289]

Recognising the challenges of understanding and predicting biological invasions (especially with vertebrates), a **Network Theory** (Figure 7) was recently proposed, which seeks to understand all aspects of invasion through the description of 'relevant anthropogenic and ecological factors'.[290]

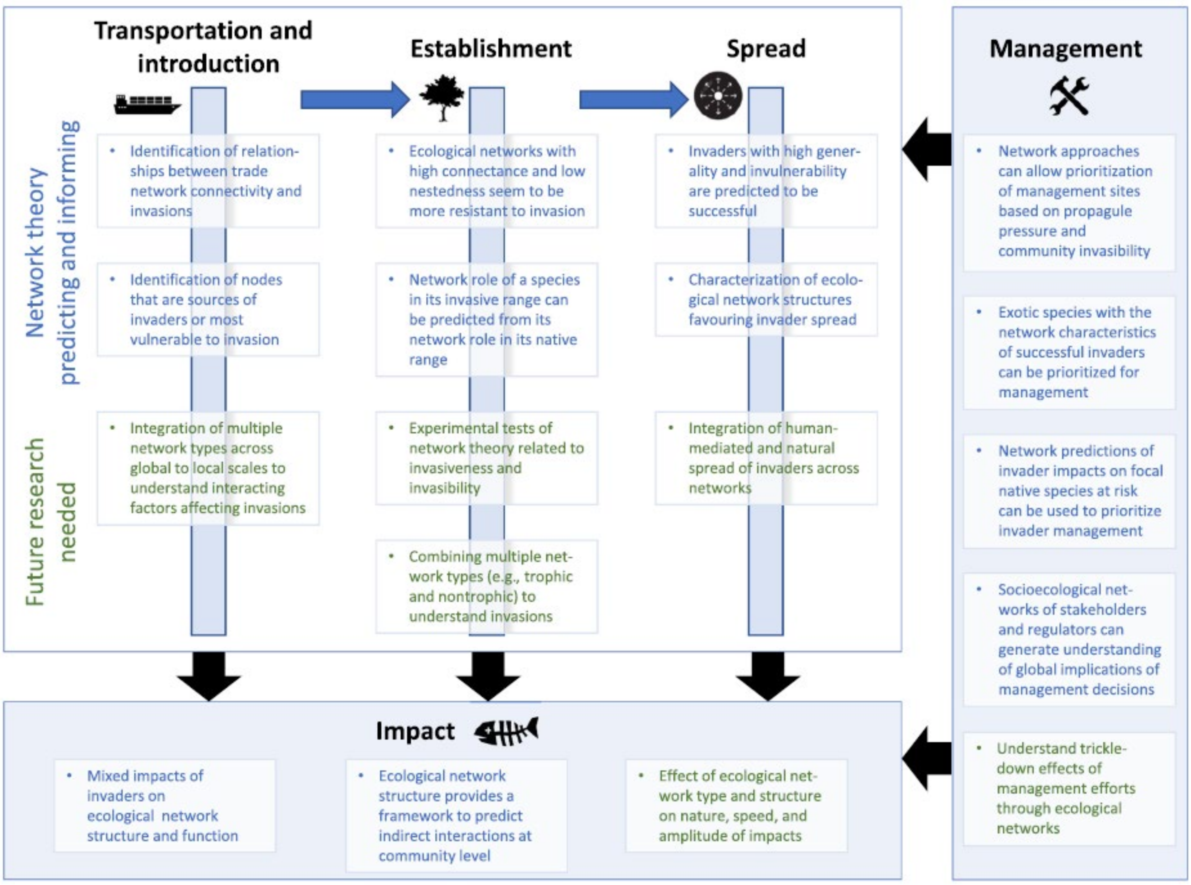

Figure 7. Network approaches can also inform predictions about ecological impact and management approaches at all stages.

Blue text describes ways that networks can be used to understand and predict invasions. Green text describes future research necessary in each area.

Source: Frost, C.M. et al., 'Using Network Theory to understand and predict biological invasions', *Trends Ecol. Evol.*, vol. 34, no. 9, 2019, pp. 831–843, fig. 1. https://doi.org/10.1016/j.tree.2019.04.012

[289] Novoa, A. et al., 'Invasion syndromes: A systematic approach for predicting biological invasions and facilitating effective management', *Biol. Invasions*, vol. 22, 2020, pp. 1801–1820. https://doi.org/10.1007/s10530-020-02220-w

[290] Frost, C. M. et al., 'Using Network Theory to understand and predict biological invasions', *Trends Ecol. Evol.*, vol. 34, no. 9, 2019, pp. 831–843. https://doi.org/10.1016/j.tree.2019.04.012

Utilising the ranges of technologies highlighted in this report effectively to recognise the 'Invasion Syndrome' in an Australian context and then applying it to the Framework proposed below (Figure 8), will allow CISS to advance understanding of vertebrate invasions and their management.

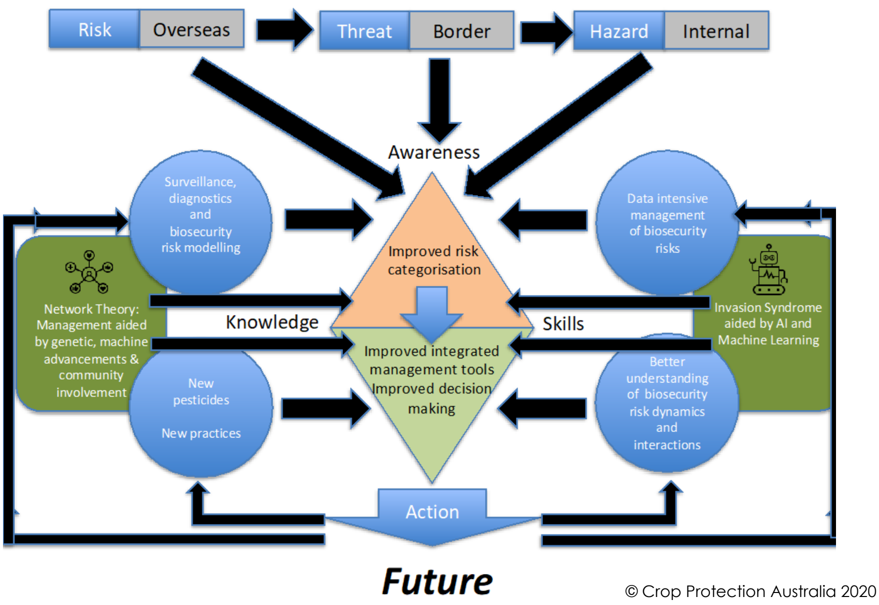

Figure 8. Network theory and Invasions syndrome approach which are gaining global traction in invasive species management.

Source: Rainbow, R., Crop Protection Australia, 2020

Early adoption of the technological advancements discussed in this report will position CISS to be a leader in effectively negating the detrimental impact of invasive vertebrate species, locally and globally, as:

> '…there is now substantial momentum behind countries delivering information on invasive species, with significant progress in the range, quality and scope of information sources, supporting tools, data infrastructure and information systems. A spirit of cooperation and knowledge exchange, and a modular approach to countries delivering information on invasive species, the necessary building blocks for a global observation and monitoring system are in place. This system enables contributions from countries across the economic development spectrum'.[291]

Taking into account the recent advancements of technological abilities, it is now crucial that additional research to further expand our knowledge in negating the undesirable impacts of pest invasions is undertaken. Additionally, achieving successful implementation of the technologies in discussion is paramount in advancing the field of management of vertebrate pest wildlife.

[291] Latombe, G. et al., 'A vision for global monitoring of biological invasions', *Biol. Conserv.*, vol. 213, Part B, 2017, pp. 295–308. https://doi.org/10.1016/j.biocon.2016.06.013.

8.1 CONCLUDING REMARKS

Biosecurity is fundamental for safeguarding our valuable agricultural resources against the threat and impacts of pests, weeds and diseases. CISS has demonstrably focused on emerging technologies and management practices that have national and international application and effectively delivered solutions through a partnership model. This report highlights that there are three main areas for continued investment:

- Greatly increasing the involvement of individuals and groups from industry, the community and government in detecting and reporting pests.
- Identifying high risk pathways and locations for pest introduction and establishment.
- Introducing innovative, low-cost technological improvements to assist in pest reporting and identification.

These areas of research should be pursued to protect Australian biodiversity from invasions by vertebrate pest species and limit impacts on both agricultural production and our rural and urban landscapes.

9 APPENDICES

APPENDIX A: INVASION SYNDROME AND CASE STUDIES

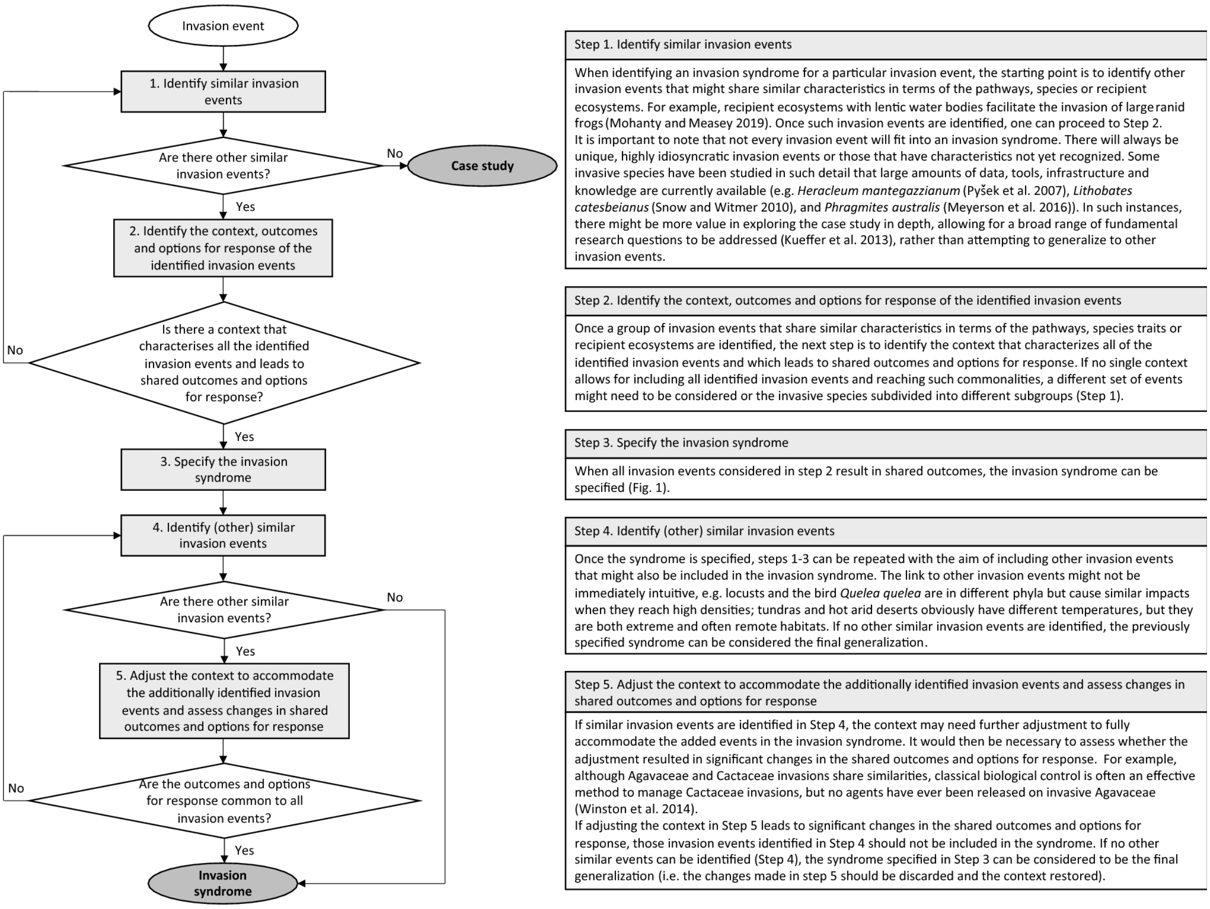

Figure 9. Schematic diagram and description of the five steps proposed for identifying invasion syndromes.

Source: Novoa, A. et al., 'Invasion syndromes: A systematic approach for predicting biological invasions and facilitating effective management', *Biol. Invasions*, vol. 22, 2020, pp. 1801–1820, fig. 3. https://doi.org/10.1007/s10530-020-02220-w

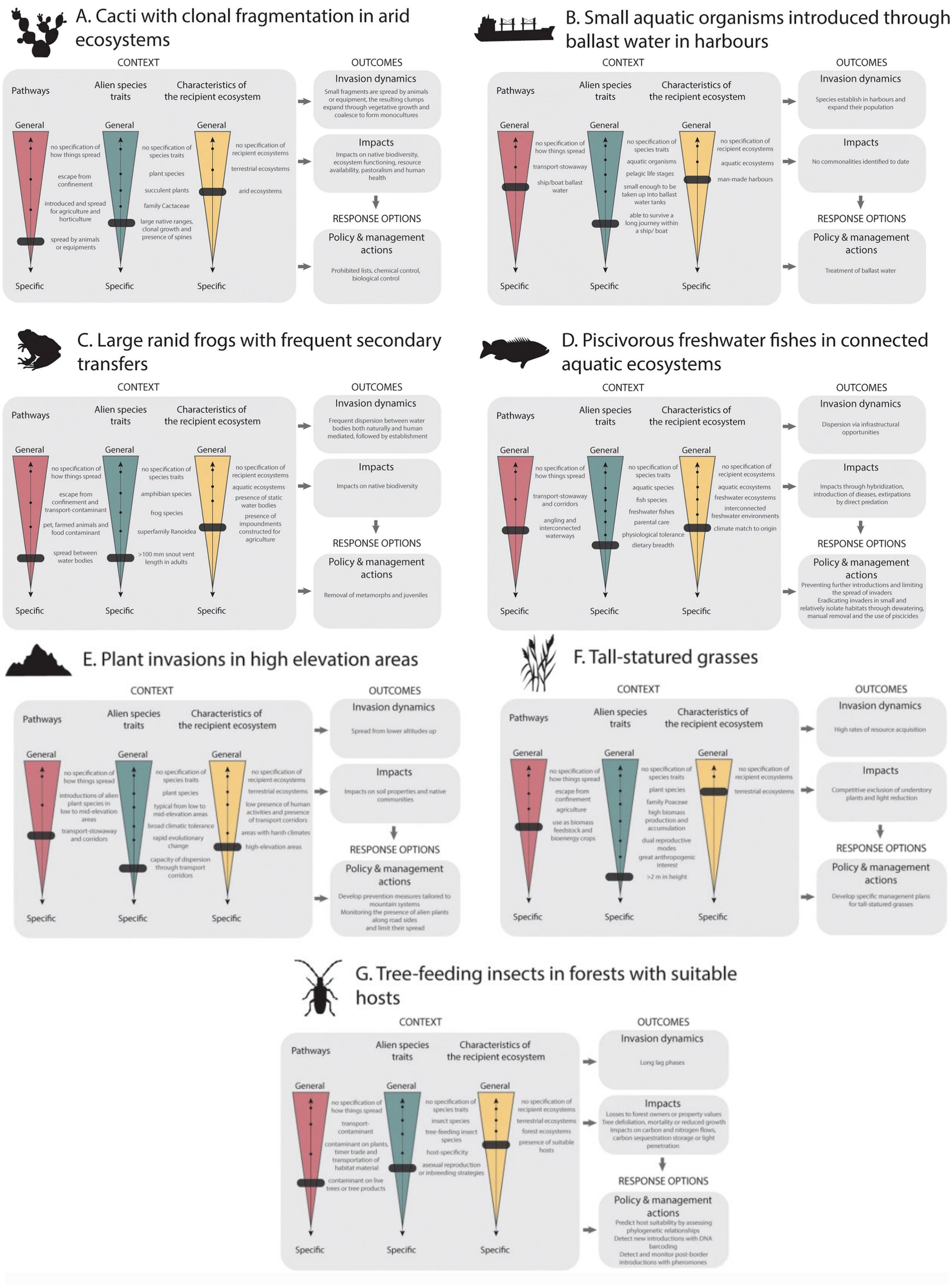

Figure 10. Examples of seven invasion syndromes proposed.

Source: Novoa, A. et al., 'Invasion syndromes: A systematic approach for predicting biological invasions and facilitating effective management', *Biol. Invasions*, vol. 22, 2020, pp. 1801–1820, fig. 2. https://doi.org/10.1007/s10530-020-02220-w

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Cameron Begley completed his undergraduate degree in Chemical Engineering then took technical sales and marketing roles in the chemical industry, initially with Dow Chemical and then Akzo Nobel Chemicals with a range of regional roles and responsibilities.

On completing an Executive MBA he then moved into technology transfer and commercialisation with CSIRO, initially linked to Chemical Engineering Sciences and then to a Commercial General Management role at the then Division of Entomology. There he was involved in business developmentc and commercial activities linked to biosecurity, agriculture and industrial biotechnology, facilitating a range of R&D and commercialisation transactions working across CSIRO, external researcher, commercial and government partnerships in seeking to catalyse Australia's bioeconomy industries.

In 2014, Cameron established Spiegare Pty Ltd, which is a consultancy focused on technology transfer and commercialisation advisory for companies, R&D investors and publicly funded research institutions.

Dr Rohan Rainbow, Managing Director, Crop Protection Australia

Rohan Rainbow, Managing Director of Crop Protection Australia, a wholly owned business of Rainbow & Associates Pty Ltd established in 2001, has over 30 years of experience in industry leadership in the fields of agronomy, agricultural engineering, precision agriculture, farming systems development, crop protection technology, breeding for biotic traits and biosecurity preparedness.

Rohan, originally from a family farm business, graduated with a Bachelor of Applied Science Agriculture in 1987 and his PhD in soil physics and mechanics in 2001. He has extensive experience in leadership, strategic planning, management and delivery of new agricultural technologies resulting in industry practice change. Rohan has overseen the development and implementation of a number of industry strategies in plant breeding, crop protection, biosecurity, food and feed safety, farming systems, precision agriculture, robotics, automation and data, including during his 7.5 years as the GRDC senior plant health manager including Theme leader - Protecting Your Crop.

With established relationships at senior levels of government, machinery, technology and chemical manufacturers, research and grower organisations, Rohan has significant experience in the delivery of reforms to national programs, technology development, agricultural industry practice change and technology adoption.

Dr Faisal Younus, Associate, Spiegare Pty Ltd

A scientist and researcher with over 8 years of experience, Faisal holds a First Class Honours degree in Biotechnology from Deakin University, Australia and a PhD degree in neuro-biochemistry from the Australian National University.

Faisal has been involved in technology and commercialisation projects globally and has also undertaken multiple projects supporting the development of policy and regulatory change to enable various industries to access new technologies and markets. His multidisciplinary research is shown by publications in international high impact scientific and educational professional journals such as *PNAS* and *Nature* with over hundreds of citations.
His scientific works have been also heavily publicised by local and international media. Winner of numerous academic and industry awards and scholarships, Faisal was heavily involved in the inaugural CSIRO Acceleration Program, pitching a 'Scientific equipment and facility access platform'. He was also the winner of the inaugural CSIRO 2020 strategy competition with his ideas being incorporated into the CSIRO 2020 Strategy Policy.

Faisal has a tremendous track record of creating organizational value by developing and executing innovative projects at both strategic and tactical levels with national and international collaborators such as Grain Research Development Corporation (GRDC), Mitsubishi Chemical Corporation (MCC), Queensland University of Technology (QUT), Sugar Research Australia (SRA), Agilent Technologies (USA) and Institut National de la Recherche Agronomique (INRA, France) and multiple ministries of the Government of Bangladesh.

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