INVASIVE SPECIES SOLUTIONS 2030
OVERVIEW OF TECHNOLOGY OPPORTUNITIES

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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.

Fortunately, science is driving 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 established invasive species.

This report 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.

As a 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 Centre for Invasive Species Solutions intrinsically embodies the shared responsibility approach to the National Biosecurity System.

Working together in large-scale RD&E collaborations through the Centre and its precursor has already delivered a pipeline of biocontrol agents, new toxins, environmental DNA detection techniques, and tools that empower and enable communities to better and more efficiently manage pest threats. The 2020s offer immense promise and potential to take our proven collaborative model to the next level so that Australia can quickly and fully take advantage of emerging technologies, especially those whose development is being propelled through health and defence applications.

This report provides a window to a range of these technologies and the solutions able to be delivered by 2030.

Dr Bruce Christie
Chair

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CEO

1 EXECUTIVE SUMMARY

The ongoing increases in economic and environmental losses caused by invasive species underpins the urgent need to identify and implement effective management practices to successfully prevent, detect, control and possibly eradicate invasive species.

Locating the presence of an invasive species at a site early in the invasion process usually requires careful and efficient monitoring. Constraints in successfully identifying invasive species makes the management process harder in the long run. Furthermore, it often leads to increased management costs and also makes the eradication of the invasive species almost impossible.

The report herein provides a landscape analysis of biosecurity and invasive species technology opportunities that could be leveraged as part of an innovation centred transformation of the National Biosecurity System. While there is a lot of data available in these spaces, it is not collated and related back to specific opportunities that could impact invasive species management.

The overview is framed around the Centre for Invasive Species Solutions (CISS) four innovation platforms and focal invasive species streams: vertebrate pests, weeds, and environmental invertebrates and diseases. The four innovation platforms 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 has reflected on current research activities in each of these platforms and provided commentary on their effectiveness and efficiency in reducing impacts of invasive species to agriculture and the environment. A thematic analysis of further technological advancements to manage invasive species (excluding agricultural invertebrates and disease) has been undertaken to enable, inform and support CISS strategy development and the subsequent platform development of ensuing investments through the identification of specific targets and technical capacity.

Chapter 2 of the report introduces megatrends with a focus on breakthrough technologies and attempts to understand the opportunities and features required to build an efficient biosecurity system. Following on, Chapter 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 and weed species, leading to possible eradication and better preparedness. The subsequent chapters – 4,5,6 and 7, examine the opportunities for the four innovation platforms identified by CISS and the role in efficient and effective management of invasive species. Many of the technologies discussed in the review have their origin in military defence and intelligence but 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 Chapter 8 discusses the findings of the report and how these will impact vertebrate pests, weeds and environmental invertebrates. This chapter also suggests how technologies could transform arrangements at different stages of the invasive invasion curve (e.g. pre-border, border, post-border eradication, containment, and asset protection).

The report highlights four key megatrends: intensification of climate variability, rapid urbanisation driven by population growth, global interconnectedness, and acceleration of technological advancements playing an integral role moving forward in effective management of invasive species. 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.

As suggested in the report, an innovative biosecurity system should be seeking to invest in the development and demonstration of products that meaningfully and simultaneously impact economic, environmental and social outcomes. Biosecurity risks, threats and hazards should be managed through a data-driven surveillance analysis and a response cycle that is dynamic in nature. Delivering long-term confidence to all the 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.

While CISS is looking at solutions at species and regional levels, there is a growing need to establish early warning systems for emerging pests leveraging the technological advancements and also encourage 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 been historically impeded by unclear value propositions for the proposed research and product solutions – a trend that needs to be addressed moving forward.

The report further highlights three main areas for improvement, as follows:

- Greatly increasing the involvement and cooperation 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, value creating technological improvements to assist in pest reporting and identification.

Australian invasive species management led by CISS needs to continue to play a necessary role in catalysing the discovery and delivery of world-leading, humane, cost-efficient, and ecologically sound controls for invasive animals. Failure to achieve this would further expose Australia’s agricultural and natural resource managers to the risk of having inadequate technologies to protect national biodiversity assets and secure long-term food security.

2 INTRODUCTION

Australia is continuingly facing growing pressure from terrestrial and aquatic pests, weeds and diseases that is posing a serious threat to the country's biodiversity, ecosystem sustainability and economy.[1] 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.[2,3] Rabbits, goats and camels prevent native desert plant community regeneration; rabbits alone impacting over 320 threatened species.[4] The impact of weeds on agricultural production and the environment, along with public and private infrastructure, is estimated to impose an overall average cost of nearly $5 billion annually across Australia. Yield loss from weed competition, combined with the cost of weed control is estimated on average at $82.7 million in sugarcane and $195.8 million in cotton[5], and $3.3 billion in grains each year, while Annual ryegrass on its own costs cereal farmers $93 million a year.[6] Aquaculture diseases have affected oysters and cost the prawn industry $43 million.[7]

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 stand 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 disruption 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.[8] The recent 2014 extinction of the Christmas Island forest skink due to invasive species highlights that they remain a major threat to Australian wildlife.[9]

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[1] 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).

[2] 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).

[3] 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

[4] 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

[5] McLeod, R., *Annual Costs of Weeds in Australia*, eSYS Development Pty Limited, Published by the Centre for Invasive Species Solutions, Canberra, Australia, 2018, https://invasives.com.au/wp-content/uploads/2019/01/Cost-of-weeds-report.pdf (accessed 01/10/2020).

[6] Llewellyn, R.S. et al., Impact of Weeds on Australian Grain Production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices, Report for GRDC, CSIRO, Australia, 2016, https://grdc.com.au/__data/assets/pdf_file/0027/75843/grdc_weeds_review_r8.pdf.pdf (accessed 01/10/2020).

[7] Inspector-General of Biosecurity, *Uncooked prawn imports: Effectiveness of biosecurity controls*, Review Report No. 2017–18/01, 2017, https://www.igb.gov.au/sites/default/files/documents/final-uncooked-prawn-imports_0.pdf (accessed 01/10/2020).

[8] 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

[9] 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, yet 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.[10, 11]

Source: Adapted from Invasive Plants and Animals Policy Framework,
State of Victoria, Department of Primary Industries, 2010.

Rapid agricultural expansion and intensification, population shift from rural to urban areas, changing

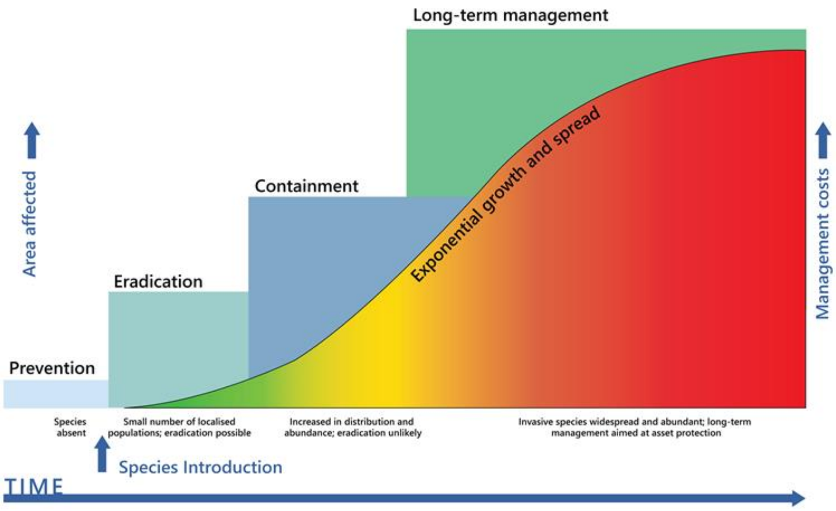

Figure 1. The invasion curve.

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. 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.

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.[12] Megatrends have the potential to irreversibly change the way we live and challenge the models we use to organise our societies.[13] A range of authors and organisations

[10] 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

[11] Tobin, P. C., ‘Managing invasive species’, *F1000Research*, *7*, F1000 Faculty Rev-1686, 2018, https://doi.org/10.12688/f1000research.15414.1

[12]. Hajkowicz, S., Global Megatrends: Seven Patterns of Change Shaping Our Future, Australia, CSIRO Publishing, 2015.

[13] 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.

around the world have undertaken studies to identify megatrends (Appendix A).[14, 15, 16, 17, 18, 19] 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 the growing population; increasing urbanisation; demographic societal and geographic climate change impacts; rapid acceleration of technology development; globalised trade yet increasing geo-political trading complexity; increasing trade regulations; 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.
- 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.

[14] 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).

[15] 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).

[16] 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).

[17] 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).

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

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

- 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

- 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.[20]

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.[21, 22] Other technologies like LiDAR (Light Detection and Ranging) show promise for differentiating species based on 3D crown structure and spatial characteristics.[23, 24] 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.[25] 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.[26] 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

[20] 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

[21] Laybros, A. et al., 'Across Date Species Detection Using Airborne Imaging Spectroscopy', *Remote Sensing*, vol. 11, no. 7, 2019, p. 789. https://doi.org/10.3390/rs11070789

[22] Kagan, P. et al., 'Multispectral Approach for Identifying Invasive Plant Species Based on Flowering Phenology Characteristics', *Remote Sensing*, vol. 11, 2019. https://dio.org/ 10.3390/rs11080953.

[23] Hastings, J. et al., 'Tree Species Traits Determine the Success of LiDAR-Based Crown Mapping in a Mixed Temperate Forest', *Remote Sensing,* vol. 12, 2020, p. 309. https://dio.org/10.3390/rs12020309.

[24] CISION PRNewswire, '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).

[25] Transon, J. et al., 'Survey of Hyperspectral Earth Observation Applications from Space in the Sentinel-2 Context', *Remote Sens*., vol. 10, no. 2, 2018, p.157. https://doi.org/10.3390/rs10020157

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

monitoring plant invasions.[27] Commercial satellites are delivering increased resolution from Planet will increase 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.[28]

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.[29, 30] 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.[31] Bayesian belief networks and decision trees have been used to classify invaders by the level of invasiveness (for alien macro-invertebrates and plants in North America, respectively).[32] 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.[33, 34, 35]

UAVs, popularly called drones, have their heritage within military defence, and until recently their development was predominantly driven by defence applications, but the adaptabilities of UAVs are now allowing these to be increasingly used for biosecurity purposes.[36] Historical examples include US military developed GPS technology, but future examples potentially include nano drone swarms that could further transform biosecurity surveillance.[37, 38, 39]

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.[40, 41] 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

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

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

[29] 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

[30] 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

[31] 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

[32] Boets, P. et al., 'Evaluation and comparison of data-driven and knowledge-supported Bayesian Belief Networks to assess the habitat suitability for alien macroinvertebrates', *Environmental Modelling and Software,* vol. 74, 2015, pp. 92-103. https://doi.org/10.1016/j.envsoft.2015.09.005.

[33] 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

[34] 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

[35] 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

[36] 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 2/10/2020).

[37] 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 2/10/2020).

[38] 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 2/10/2020).

[39] 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.

[40] 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

[41] 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

in humans. Likewise, anti-*Plasmodium falciparum* CRISPR systems have been implemented in the Asian malaria vector *Anopheles stephensi*.[42, 43]

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.[44] 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.[45] It should be noted that vertebrates such as rodents may also digest RNA nanoparticles, which may possibly serve as a delivery vehicle.[46] 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.[47] 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.[48]

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 (See also Appendix B).[49, 50]

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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42 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

43 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

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

45 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

46 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

47 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.

48 Palmer, C. P., 'Can technology save life on Earth?', *World Economic Forum* [website], 10 September 2018, https://www.weforum.org/agenda/2018/09/can-technology-save-life-on-earth/ (accessed 15/08/2020).

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50 Kompas, T., Chu, L., Van Ha, P. & Spring, D., '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

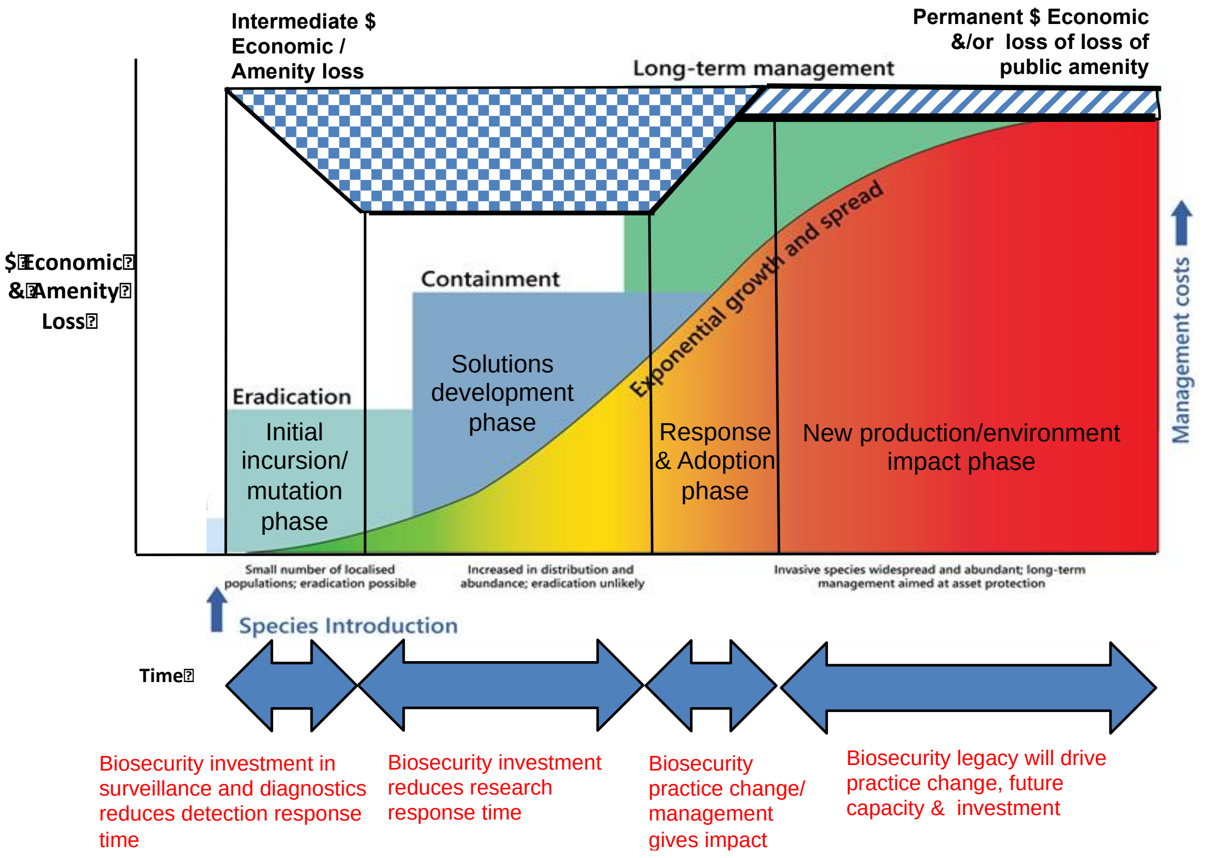

Figure 2. Value proposition for pre-emptive biosecurity investment and legacy impacts.

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,

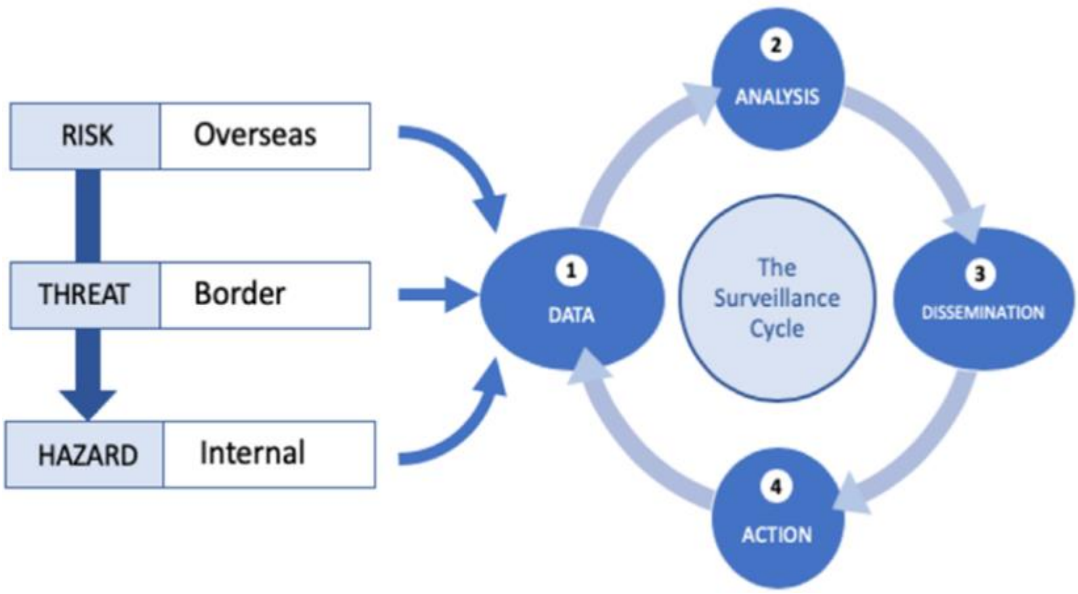

Figure 3. The role of emerging technologies on biosecurity system.

threats and hazards should be managed in a data-driven surveillance analysis and action cycle as suggested below (Figure 3).[51]

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, current 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 is in good accordance with the recently published report on the role of emerging technologies on Australian biosecurity system (Figure 4).[52]

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

[52] Animal Health Australia (AHA), Megatrends, opportunities and challenges facing Australian livestock industries, 2019.

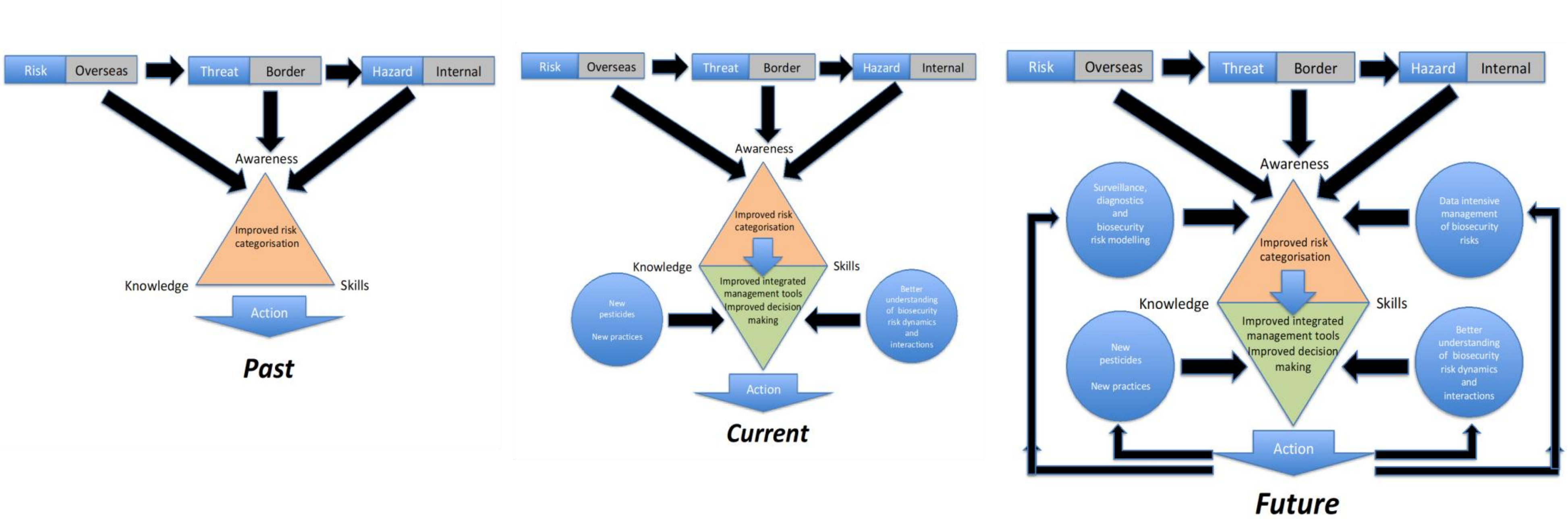

Figure 4. The role of technology and innovation in an advanced biosecurity system.

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

Supporting the delivery of products to meet biosecurity challenges should stand 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 a landscape analysis which overviews biosecurity technology opportunities that could be leveraged as part of an innovation-centred transformation of the National Biosecurity System, particularly as they relate to the Centre's five innovation platforms and three invasive species streams. While there is a lot of data available in these spaces, it is not collated and related back to specific opportunities that could impact invasive species management.

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 impacts of invasive species to agriculture and the environment. A thematic analysis of further technological advancements to manage invasive species (excluding agricultural invertebrates and disease) will be undertaken to inform and support CISS strategy development and the subsequent platform development of ensuing investments through the identification of specific targets and technical capacity.

2.5 STRUCTURE OF REPORT

Chapter 2 of the report introduces megatrends with a focus on breakthrough technologies and attempts to understand the opportunities and features required to build an efficient biosecurity system. Following on, Chapter 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 and weed species, leading to possible eradication and better preparedness.

The subsequent chapters – 4,5,6 and 7, examine the opportunities for the four innovation platforms identified by CISS and its role in efficient and effective management of invasive species. The final Chapter 8 discusses the findings of the report and how it will impact vertebrate pests, weeds and environmental invertebrates. This chapter also suggests how technologies could transform arrangements at different stages of the invasive invasion curve (e.g. pre-border, border, post-border eradication, containment, and asset protection).

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 the 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).

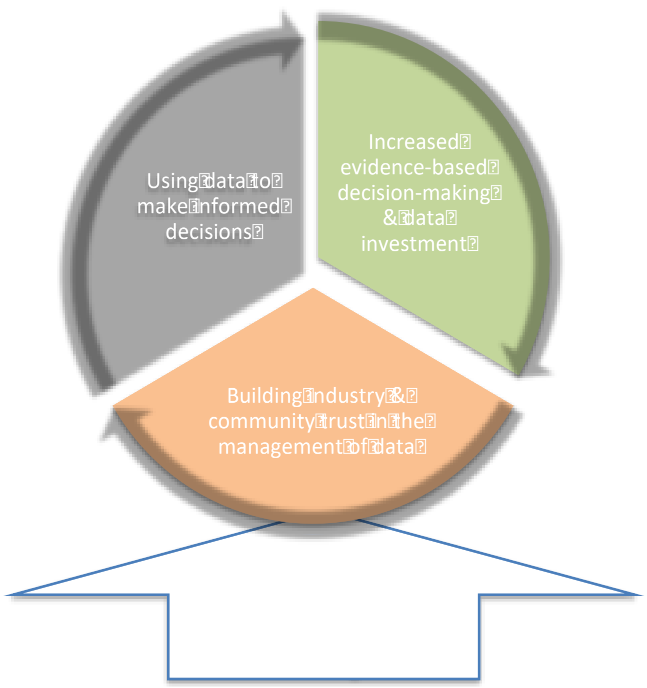

Figure 5. Key components that underpin informed decision making using digital data.

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 is 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 such as *iMapPests*[53] is 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[54], native[55] and pest animals[56], 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.

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

54 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).

55 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).

56 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, improving our understanding of the drivers, processes, patterns, and impacts of invasive species.[57, 58] Remote sensing has been particularly useful to identify and map animal and plant invaders[59, 60] as well as to predict their current and future potential distributions and impacts.[61] 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 (Appendix C).[62]

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.[63] Another example includes the use of thermographic imaging techniques in agroforestry to detect nests of the invasive Asian hornet (*Vespa velutina*).[64]

Remote sensing can be an effective tool to detect alien weeds (e.g. alien herbs and shrubs), pests and diseases (e.g. insects) at cultivation sites. Examples include high-resolution imagery to detect and classify buffelgrass (*Pennisetum ciliare*)[65] and the detection of beetle infestations in fir forests[66]. Also, when included in statistical modelling approaches, remote sensing data can be used to detect species able to escape from cultivation sites and predict their potential areas of invasion.[67]

Understanding feedback loops between soil biota and alien species is emerging as a pressing issue in invasion ecology.[68] The field of soil remote sensing has been progressing greatly over the last decades. Modern remote sensing offers many approaches to monitor 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.[69] 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.[70]

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

[59] 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

[60] 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

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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 are now at a 1 km resolution,[71] and have 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 accessible, comprehensive, high-resolution (3 and 9 km) soil moisture data.[72] *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.[73] 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.[74] 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.[75]

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 animals' movements with unparalled 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.[76]

Indirect **satellite surveillance** methods are another alternative to study weed invasion.
A study mapped Siam weed (*Chromolaena odorata*) in the understory using Landsat ETM+ and an artificial neural network to predict forest density and canopy light penetration and then subsequently predict Siam weed seed production. They found that 93% of the invasive seed production was predicted by the light intensity reaching the understory and concluded that this method worked relatively well to detect the weed, despite the spatial resolution limiting detection to well-established weed patches.[77]

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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[78], the number of eDNA studies published has exponentially increased, and many government agencies have established eDNA-based monitoring programs[79].

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.[80] Both LAMP and qPCR methods are considered superior to other available molecular diagnostic techniques and are very similar in terms of sensitivity and specificity.[81] [82] Most importantly, advancements in LAMP and qPCR-based technologies have made these methods suitable to field applications outside laboratory settings, where the availability of battery-powered portable platforms such as the LAMP-based *Genie*® II (Optigene, UK)[83] or the qPCR-based *Franklin*™ Thermocycler (Biomeme (USA)[84], 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.[85] 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.

LAMP and qPCR-based genetic identification has been shown to be useful for quickly identifying insects intercepted at airports [86], insects detected in traps[87], and even for identifying insects from

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[78] 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

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[87] Chinellato, F. et al., 'Smart-traps combined with molecular on-site detection to monitor *Monochamus* spp. and associated pine wood nematode', in Schröder, T. (ed.), *Pine Wilt Disease Conference, 15-18 October 2013, Braunschweig,* 2013, pp. 23–25. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.978.3223&rep=rep1&type=pdf

traces (i.e. faecal pellets or frass) found on wood packaging[88] and grain products[89]. The University of Canberra is now evaluating the Biomeme *Franklin* platform for a pre-border use case involving ornamental fish. [90] [91] [92] This includes the detection of pathogens and parasites in the live ornamental fish trade using environmental DNA (eDNA) techniques, which has the potential to hugely improve current biosecurity practices.[93]

Environmental DNA (eDNA) has also become an effective approach for the early detection of *Didymosphenia geminate* in the United States,[94] and as it is a national priority exotic environmental biosecurity pest, has potential in Australia.

On the other hand, NSW Department of Primary Industries (DPI) scientists, recently developed a field kit which uses LAMP technology to identify serrated tussock and Chilean needle grass in the field. Further development of the technology could see the method modified for diagnostics of other target weeds, insect pests and pathogens.[95]

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] 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

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95 Department of Primary Industries (DPI) – NSW, 'LAMP lights way to pre-emptive weed strikes', *DPI – NSW* [website], 16 July 2019, https://www.dpi.nsw.gov.au/about-us/media-centre/releases/2019/lamp-lights-way-to-pre-emptive-weed-strikes (accessed 2/10/2020).

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, 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.

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 mammalian 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 Iberian carnivores from faecal DNA, including invasive mammals such as the genet *Genetta 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 *Perca fluviatilis* (redfin perch), 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 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

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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] Recently, **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. 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.[118]

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 [119],[120],[121] and they hold the potential to be also developed for invasive 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.[122]

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[111] Hebert, P.D.N., Cywinska, A., Ball, S.L. & deWaard, J.R., 'Biological identifications through DNA barcodes', *Proc. Biol. Sci. B.,* vol. 270, no. 1512, 2003, pp. 313–321. https://doi.org/10.1098/rspb.2002.2218

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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.[123] 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[124], detector dogs have been successfully demonstrated to detect bird carcasses resulting from impacts with anthropogenic structures[125], identifying animal parts in illegal wildlife trafficking, and uncovering of invasive species. Dogs have also been used to rapidly detect the signs of small to large invasive mammals, including rabbits on Macquarie Island[126], feral cats[127], nutria[128], and mongooses[129]. 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.[130] However, detector dogs have also effectively discovered a variety of other invasive taxa, including Dreissenid mussels[131], brown tree snakes and Burmese pythons[132], insects[133], and invasive weeds[134] (including in eradication programs[135]). 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.[136]

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,

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and wood rot caused by pathogenic fungi.[137, 138, 139] 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,[140] including those emitted by plants when vegetative tissues are damaged by invasive species.[141]

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.[142, 143] 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 plants and 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 and monitor the invasive brown tree snake (*Boiga irregularis*), where it has known to negatively impact the islands' native bird fauna.[144]

In Australia, a machine learning innovative software tool, *ClassifyMe* was recently designed and provides users the opportunity to utilise state-of-the-art image recognition algorithms without the need for specialised computer programming skills.[145] *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.

AI researchers from Microsoft and CSIRO joined forces to design an **AI model** that can identify an invasive species called para grass, found throughout Kakadu National Park in Australia. Para grass is a fast-growing weed that can spread rapidly, quickly displacing many native plants in a region. The researchers utilised images collected by drones, and once the model was trained on the labelled images it was able to successfully identify para grass, allowing the researchers to remove it from vulnerable wetlands. This had the effect of allowing thousands of magpie geese to return to the region.[146] A new AI system that can quickly survey large and inconvenient areas for invasive and potentially damaging plant species is being developed by UK Centre for Ecology and Hydrology (UKCEH) and Keen AI, a Birmingham-based artificial intelligence and machine learning company.[147] New South Wales (NSW) and Victorian run weed eradication programs in Australia regularly utilising drones in the orange hawkweed eradication operation, as large and remote areas can be surveyed at

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144 Klein, D.J., McKown, M.W. & Tershy, B.R., 'Deep learning for large scale biodiversity monitoring', *Bloomberg Data for Good Exchange Conference*, 2015, https://ccal.ucsc.edu/wp-content/uploads/2017/03/Klein_2015.pdf (accessed 02/10/2020).

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147 Williams, S., 'AI system could identify roadside invasive species', *UK Centre for Ecology & Hydrology* [website], 16 June 2020, https://www.ceh.ac.uk/press/ai-system-could-identify-roadside-invasive-species

low cost.[148] CISS is currently developing a weed identification app using computer vision and a reporting and information system *WeedScan*, with the app leading the user to the specific weed information and reporting interface provided by *WeedScan*.[149]

The application of thermal sensors to ecological and wildlife monitoring purposes has been keenly investigated by researchers over the years.[150, 151, 152, 153, 154] 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.[155] 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.[156]

Technological advancements are facilitating **acoustic detection** of organisms that were previously far less audible to the human ear[157]. For example, acoustic sensors (piezoelectric sensors, lasers, Doppler vibrometers, ultrasound microphones) are currently being used to monitor rodents and insect pests in grain shipments.[158] 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.[159]

Examples can also be found for vertebrates such as development of acoustic detection technology for Asian house gecko as part of the Gorgon project.[160] CISS is investing in the development of a cost-

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effective remote acoustic surveillance, detection and reporting solution[161] using Western Australia's starling control program as an initial case-study.[162]

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.[163] 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. Interestingly, researchers at the Queensland University of Technology created an autonomous robot, the *COTSbot*, equipped with machine vision, stereoscopic cameras and a pneumatic injection arm.[164] The robot is designed to identify and kill invasive Crown-of-thorns starfish in the Great Barrier Reef and serves as a powerful rapid response device for both newly introduced species, and species that are well-established where human-led eradication efforts have failed. Additionally, The University of Sydney has built an autonomous weeding robot which will have a series of cameras to determine precisely when to treat weeds.[165]

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 through ballistic application of herbicides.[166] Drones can potentially replace aircraft in carrying enhanced sensor packages like LIDAR, which cost-effectively detects the distribution of invasive plant species with a high degree of precision.[167] Drones are also touted to be adopted for invasive rodent eradication programs.[168]

Australian company, Ninox Robotics, is developing a high-tech surveillance by utilising UAVs with advanced real-time thermal imaging capabilities to detect invasive pests, such as 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 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.[169]

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 drones

[161] CISS, 'Automated detection: triggering smarter, faster, better response to incursions', CISS [website], 2017, https://invasives.com.au/research/automated-detection-triggering-smarter-faster-better-response-to-incursions/ (accessed 03/10/20).

[162] Juanes, F., 'Visual and acoustic sensors for early detection of biological invasions: Current uses and future potential', Journal for Nature Conservation, vol. 42, 2018, pp. 7-11, https://doi.org/10.1016/j.jnc.2018.01

[163] Cantrell, B., Martin, L. & Ellis, E.C., 'Designing autonomy: Opportunities for new wildness in the Anthropocene', Trends Ecol. Evol., vol. 32, no. 3, 2017, pp. 156-166. https://doi.org/10.1016/j.tree.2016.12.004

[164] QUT, 'Eliminating invasive reef species: COTSbot and RangerBot', QUT – Reef Research [website], n.d., https://research.qut.edu.au/reefresearch/our-research/eliminating-invasive-reef-species-cotsbot-rangerbot/ (accessed 15/08/2020).

[165] AUSVEG 'Advancing robotics in the Australian vegetable industry', AUSVEG [website], 8 April 2020, https://ausveg.com.au/articles/advancing-robotics-in-the-australian-vegetable-industry/ (accessed 03/10/20).

[166] 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

[167] Barbosa, J. et al, 'Hemiparasite: host plant interactions in a fragmented landscape assessed via imaging spectroscopy and lidar', Ecol. Appl., vol. 26, 2016, pp. 55–66. doi: 10.1890/14.2429.1/suppinfo

[168] BBC, 'Drones help Galapagos tackle rat infestation', BBC News [website], 31January 2019, https://www.bbc.com/news/technology-47071513 (accessed 15/08/2020).

[169] Gentle, M. et al., 'A comparison of unmanned aerial vehicles (drones) and manned helicopters for monitoring macropod populations', Wildlife Research, vol. 45, no. 7, 2018, pp. 586-594. https://doi.org/10.1071/WR18034

for crop, disease and pest monitoring.[170] Drones have been taking to WA wheatbelt skies to improve surveillance through *Optiweed*, a unique weed mapping and detection platform, to the detection of skeleton weed.[171] Crop diseases have also been monitored using mobile trapping units with different air samplers that can sample airborne pests and diseases.[172] Some of these samplers could be potentially be adapted for drone use.

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, thanks 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

[170] Gardiner, B., 'Drones being trialled to tackle Australia's pest problem', *The Conversation* [website], 21 July 2015, https://theconversation.com/huge-locust-swarms-are-threatening-food-security-but-drones-could-help-stop-them-140625 (accessed 15/08/2020).

[171] Department of Primary Industries and Regional Development (DPIRD) WA, 'Skeleton weed under drone spotlight', *DPIRD WA* [website], 6 June 2019, https://www.agric.wa.gov.au/news/media-releases/skeleton-weed-under-drone-spotlight (accessed 06/10/2020).

[172] iMapPESTS, *iMapPESTS* [website], n.d., https://www.imappests.com.au/ (accessed 06/10/2020).

[173] Jackson, R., 'Small is beautiful: Nano drone tech is advancing', *Defence IQ* [website], 20 July 2017, https://www.defenceiq.com/defence-technology/articles/nano-drone-tech-is-advancing (accessed 15/08/2020).

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[175] Manning, P. & Jackson, M., 'The next invasion of insect pests will be discovered via social media', *The Conversation* [website], 14 August 2020, https://theconversation.com/the-next-invasion-of-insect-pests-will-be-discovered-via-social-media-143527 (accessed 15/08/2020).

[176] Wallace, R. et al., 'Workshops increase invasive species reports to EDDMapS in the Mid-Atlantic United States', *bioRxiv* 620138, 2019. https://doi.org/10.1101/620138

[177] Rateni, G., Dario, P., & Cavallo, F., 'Smartphone-based food diagnostic technologies: A review', *Sensors vol. 17,* no. 6, 2017*,* p. 1453. https://doi.org/10.3390/s17061453

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]

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, like 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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[178] AppAdvice, Home Page, *AppAdvice* [website], n.d., https://appadvice.com/app/field-guide-to-pest-animals/634197149 (accessed 15/08/2020).

[179] Invasive Species, 'Bring the Power of EDDMapS to Your Smartphone', *Invasive Species – Cooperative Extensions-USDA* [website], 24 July 2019, https://invasive-species.extension.org/bring-the-power-of-eddmaps-to-your-smartphone/ (accessed 15/08/2020).

[180] Froud, K.J. et al., 'Passive surveillance of new exotic pests and diseases', in Froud, K.J., Popay, A.I. & Zydenbos, S.M. (eds), *Proceedings of a Symposium on Surveillance for Biosecurity Symposium: Pre-border to Pest Management*. The NZ Plant Protection Society, 2008, pp 97–110. https://nzpps.org/_oldsite/books/2008_Surveillance/Surveillance.pdf (accessed 06/10/2020).

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[183] Figueroa-Alfaro, R.W. & Tang, Z., 'Evaluating the aesthetic value of cultural ecosystem services by mapping geo-tagged photographs from social media data on Panoramio and Flickr', *J. Environ. Plan. Manag.*, vol 60, no. 2, 2017, pp. 266–281. https://doi.org/10.1080/09640568.2016.1151772

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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:[186],[187],[188]

- **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 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.

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]

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

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[185] Kenis, M., et al., ‘Classical biological control of insect pests of trees: facts and figures’, *Biol. Invasions*, vol. 19, 2017, pp. 3401–3417. https://doi.org/10.1007/s10530-017-1414-4

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[190] Strive, T. & Cox, T.E., ‘Lethal biological control of rabbits: The most powerful tools for landscape-scale mitigation of rabbit impacts in Australia’, *Australian Zoologist*, vol. 40, vo. 1, 2019, pp. 118-128. https://doi.org/10.7882/AZ.2019.016

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[193] Stiling, P., ‘Potential nontarget effects of a biological control agent, Prickly Pear Moth, *Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae), in North America, and possible management actions’, *Biological Invasions,* vol. 4, 2002, pp. 273-281. https://doi.org/10.1023/A:1020988922746

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. This has been complemented by an important national rabbit disease monitoring program to measure biocontrol efficacy and 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.[194] 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.[195]

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

- **Sterile release**: A technique that involves sterilization and release of males into wild populations of the same species can be useful in the control of invasive or pest species.[196]

- **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.[197]

- **Trojan Female Technique**: The 'Trojan Female Technique' is where females pass on genes that make male offspring infertile.[198] 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.

- **RNAi**: A biological process that involves RNA molecules inhibiting gene expression or translation by neutralizing targeted messenger RNA molecules through an increase or decrease in their activity.[199] 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'.[200]

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[200] 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

Recently, there has been great excitement around the possibility of using synthetic gene drives as a tool for pest control in general,[201],[202] and for biodiversity conservation in particular.[203] **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').[204] Researchers have proposed using gene drives to better control insect-borne pathogens[205] by inserting deleterious traits into an invasive population, thereby lowering overall fitness of the population. Examples include conferring 'sex ratio distortion' drive in invasive species resulting in fertile offspring of only one sex.[206] The release of a limited number of these modified individuals into a natural population are highly controversial as it has potential 'to eventually breed that population out of existence'.[207] Gene drives may offer viable suppression for wasps and other haplodiploid pests and are being investigated as a strategic control for European and other related wasps in New Zealand, which is also a significant problem in Australia.[208]

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.[209]

Research is progressing to demonstrate proof of concept of this platform technology in a mouse model.[210],[211] If successful, this transformational technology could potentially be applied to a number of vertebrate pests, such as rabbits and feral cats.[212],[213] Other potential target pests include cane toads.[214]

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

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[214] Tingley, R. et al., 'New Weapons in the Toad Toolkit: A review of methods to control and mitigate the biodiversity impacts of invasive Cane Toads (*Rhinella Marina*)', *Quarterly Review of Biology*, vol. 92, no. 2, 2017, pp. 123-49. https://doi.org/10.1086/692167

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.[215]

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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 5.4) in focal areas of the landscape.[216] 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.[217]

Landscape-scale approaches to wildlife management have long been adopted in marine and terrestrial conservation biology[218,219], motivated by the loss of wildlife populations in degraded and fragmented landscapes and seascapes[220]. 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.[221,222,223]

New technologies, such as drones (discussed above) and nanosatellites, ensures surveillance, detection, and identification of an invasive species on a landscape-scale as it spreads and expands its range, especially in uncharted areas.[224] 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.[225] The technologies described later this section, if scaled, offer the prospect to better detect and monitor invasive species over sizable geographic ranges.

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 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 like improved battery life,

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[224] 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

[225] 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.

improved sensor capabilities and real-time data analysis are all being used in IoT deployments.[226] Because of the connected ecosystem developed by evolving smartphones, citizen scientists are also playing a critical role in early detection of invasive species.[227]

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.[228],[229] Readily available **low-cost sensor components** and **microcontrollers** (e.g. Arduino, Adafruit, and Raspberry Pi) are also continually improving and expanding data collection capabilities.[230] 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 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 for example as seen in the case of projects such *Wild Dog Alert*.[231],[232] There are also cableless 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.[233]

6.3 NEW TOOLS: NANOSATELLITES

Small, low-cost **nanosatellite** constellations offer an alternative method to drones and satellites for collecting remote-sensing data.[234] Traditional earth observation satellites such as Landsat 8 costs approximately $900 million and require a 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 nanosatellite platforms must generally be smaller and operate with reduced power, and there are data analysis and integration challenges.[235]. 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.[236]

[226] NEC, 'Organizations Are Turning to Technology to Save the World's Most Threatened Animals', *NEC* [website], 28 February 2020, https://www.nec.com/en/global/insights/article/2020022502/index.html (accessed 15/08/2020).

[227] Swanson, A., Kosmala, M., Lintott, C. & Packer, C., '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

[228] Guo, S. et al, 'The application of the Internet of Things to animal ecology', *Integr. Zool*., vol. 10, 2015, pp. 572–578. https://doi.org/10.1111/1749-4877.12162

[229] Hart, J.K. & Martinez, K., 'Toward an environmental Internet of Things', *Earth Sp. Sci*., vol. 2, 2015, pp. 194–200. https://doi.org/10.1002/2014EA000044

[230] Oliveira-Jr, A. et al., 'IoT sensing platform as a driver for digital farming in rural Africa', *Sensors, vol. 20, no. 12,* 2020, p. 3511. https://doi.org/10.3390/s20123511

[231] Guo, S. et al., 2015.

[232] 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

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

[234] 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

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

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.[237] 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'.[238]

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 approaches, such as 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, now encompass ~66,000 km^2 of protected livestock grazing land in Central-Western Queensland alone.[239] 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.[240] The widespread use of successive 1080 baiting, particularly in Australia and New Zealand, has meant that populations of 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.

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237 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).

238 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).

239 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

240 National Parks & Wildlife Service NSW Government, 'National Parks and Wildlife Service aerial baiting program 2020', *National Parks & Wildlife Service 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).

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, foxes, feral cats[241], and stoats[242]. The mode of action is described as:

> *Once it is eaten and absorbed into the bloodstream, PAPP works by converting normal haemoglobin in red blood cells to methaemoglobin, which cannot carry oxygen to the heart muscles and brain. Affected animals become lethargic and sleepy before quickly becoming unresponsive and dying.*[243]

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.[244]

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.[245] Feral cat grooming traps (e.g. *Spitfire*[246], *Felixer*[247]) 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. The efficacy of these alternative control tools relies on the behavioural patterns of the target species (i.e. biting and pulling for the canid pest ejectors, lure investigation and scent marking, etc.), and to varying degrees, such devices could also impose selection on the populations being targeted.

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), also recently became commercially available.

An emerging additional option are toxins extracted directly from New Zealand plants as potential new tools.[249] 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

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241 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

242 Eason, C. et al., 'Diphacinone with cholecalciferol for controlling possums and ship rats', *New Zealand Journal of Zoology*, vol. 47, no. 2, 2020, pp. 106-120. https://doi.org/10.1080/03014223.2019.1657473

243 Pest Smart, 'Wild dogs', *PestSmart-CISS* [website], n.d., https://pestsmart.org.au/papp-for-wild-dog-and-fox-control/ (accessed 15/08/2020).

244 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).

245 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

246 Eason, C. et al., 'Diphacinone with cholecalciferol for controlling possums and ship rats', *New Zealand Journal of Zoology*, vol. 47, no. 2, 2020, pp. 106-120. https://doi.org/10.1080/03014223.2019.1657473

247 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

248 Allsop Sinéad, E. et al., 'Reduced efficacy of baiting programs for invasive species: some mechanisms and management implications', *Pacific Conservation Biology,* vol. 23, 2017, pp. 240-257. https://doi.org/10.1071/PC17006

249 Pauling, C. et al., *Matauranga rakaupaitini: Naturally occurring toxins in NewZealand plants with potential for vertebrate pest control*, Report prepared for Nga Pae o te Maramatanga, Contract No. 50, University of Auckland, 2009.

are currently exploring the potential of natural New Zealand toxins, with a current focus on tutin, the active ingredient in Tutu.[250]

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.[251]

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.[252]

Weed management is a key factor for current broadacre field crop production systems, which drives farm business decision-making, crop rotation and variety choice. There is a strategic need for new herbicides of a different and preferably new mode of action as part of an Australian resistance management and weed control strategy. With the increased incidence of herbicide resistance to many of the key herbicide modes of action (MOA) (including glyphosate), particularly due to the dependence in herbicide tolerant (HT) crops, there has been a global focus on the development of new herbicides and GM HT traits including a focus on inhibitors of hydroxyphenylpyruvate dioxygenase (HPPD) and inhibitors of protoporphyrinogen oxidase (PPO). There has not been a new mode of action discovered for over 30 years, however Bayer has recently publicly indicated the discovery of a new mode of action as a potential replacement for glyphosate.[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, offering widespread and substantial benefits to agriculture and the environment. Similar fences are proposed for more arid areas in

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[250] Ogilvie, S. et al., ‘Tutu a toxic NZ plant with promise as an animal pest control tool’, *Te Putara*, vol. 22, 2011, p. 5.

[251] Jay-Smith, M. et al., ‘Stereoselective synthesis of the rat selective toxicant norbormide’, *Tetrahedron*, vol. 72, no. 35, 2016. https://doi.org/10.1016/j.tet.2016.07.014

[252] Eason, C. et al., ‘Diphacinone with cholecalciferol for controlling possums and ship rats’, *New Zealand Journal of Zoology*, vol. 47, no. 2, 2020, pp. 106-120. https://doi.org/10.1080/03014223.2019.1657473

[253] Bandoim, L., ‘Bayer finds new herbicide molecule amid more lawsuits’, *Forbes* [website], 17 February 2020, https://www.forbes.com/sites/lanabandoim/2020/02/17/bayer-finds-new-herbicide-molecule-amid-more-lawsuits/#307815fc6173 (accessed 03/10/2020).

[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).

southern rangelands of WA.[256] Cluster fences have rapidly being 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]

[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).

[257] 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, E1550. https://doi.org/10.3390/ani10091550

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 utilize 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 recognized 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 scrutinize 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 (Appendix D).
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, that create opportunities for anyone to participate in ecological research. Smartphones, equipped with microphones and adequate computational power for acoustic monitoring

[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', *Global Ecology and Conservation*, vol. 21, 2020, e00812. https://doi.org/10.1016/j.gecco.2019.e00812

[259] Bradter, U. et al., 'Can opportunistically collected Citizen Science data fill a data gap for habitat suitability models of less common species?', *Methods Ecol. Evol*., vol. 9, 2018, 1667e1678. https://doi.org/10.1111/2041-210X.13012.

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[261] Balmford, A. et al., 'Walk on the Wild Side: Estimating the global magnitude of visits to protected areas', *PLoS Biol*, vol. 13, 2015, pp. 1–6. https://doi.org/10.1371/journal.pbio.1002074

[262] Lewandowski, E. & Specht, H., 'Influence of volunteer and project characteristics on data quality of biological surveys', *Conserv. Biol*., vol. 29, no. 3, 2015, pp. 713–723. https://doi.org/10.1111/cobi.12481

[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., Kosmala, M., Lintott, C. & Packer, C., '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).

of invasives such as certain species of birds[267], are facilitating rapid growth in the population of 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) has been known to utilise citizen scientists in addressing invasive species. According to a recent study:

> '…*the Center's suite of Bugwood mobile apps has capitalized on the ubiquity of smartphones plus the public's interest in pest and invasive species. Many of the apps are dedicated to both early detection and rapid response. For example, the Squeal on Pigs app provides services to both landowners and state officials to effectively work together to report and eradicate feral pig populations. In Florida, users can report real-time sightings of live invasive species, like Burmese python and melaleuca trees, through the IveGot1 app'*.[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] An Australian analogue targeted at invasive invertebrates and weeds is the *MyPestGuide Reporter App*.[276]

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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

268 Stockwell, S. & Gallo, S., 'Citizen science and wildlife conservation: lessons from 34 years of the Maine Loon count', *Maine Policy Review*, vol. 26, no. 2, 2017, pp. 25–32. https://digitalcommons.library.umaine.edu/mpr/vol26/iss2/6

269 Public Lab, 'MapKnitter', *Public Lab* [website], n.d., https://publiclab.org/wiki/mapknitter (accessed 15/08/2020).

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).

272 Roy-Dufresne, E. et al., 'Modeling the distribution of a wide-ranging invasive species using the sampling efforts of expert and citizen scientists', *Ecol. & Evol.,* vol. 9, no. 19, 2019, pp. 11053-11063. https://doi.org/10.1002/ece3.5609

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

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

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

276 Department of Primary Industries and Regional Development Western Australia (DPIRD WA), 'MyPestGuide Reporter', *DPIRD WA* [website], n.d., https://www.agric.wa.gov.au/apps/mypestguide-reporter (accessed 23/10/2020).

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[277]) 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.

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).[278]

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.[279]

Technological innovation combined with interdisciplinary collaboration is being applied through ideation events, hackathons, and crisis mapping to provide innovative solutions to societal problems.[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 'to 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] Olsen, P., *Australia's Pest Animals: New Solutions to Old Problems*, Bureau of Resource Sciences and Kangaroo Press Pty Ltd, NSW, 1998.

[278] 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).

[279] Martin, P. et al., *Effective Citizen Action on Invasive Species: The Institutional Challenge*, Invasive Animals Cooperative Research Centre, Canberra, 2016.

[280] 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

[281] NASA SpaceApps, 'Trace Invaders', *Space Apps* [website], n.d., https://2017.spaceappschallenge.org/challenges/our-ecological-neighborhood/trace-invaders/details (accessed 15/08/2020).

[282] Avvenuti, M., Cresci, S., Del Vigna, F. & Tesconi, M., 'Impromptu crisis mapping to prioritize emergency response', *Computer,* 2016, pp. 28–37. https://www.iit.cnr.it/sites/default/files/Avvenuti,%202016,%20Impromptu%20crisis%20mapping%20to%20prioritize%20emergency%20response.pdf (accessed 15/08/2020).

8 DISCUSSION AND CONCLUSION

This report provides an overview of a range of technology and system level opportunities to strengthen invasive species management to develop and deploy integrated biosecurity technology systems. There is a strategic opportunity to develop a trans-disciplinary, innovation-centred National Biosecurity System that addresses all phases of the invasion curve. Surveillance, monitoring and the data management systems are all critical to biosecurity technology integration. These underpin an intelligence rich approach to strategic and holistic invasive species management targeting vertebrate pests, weeds, and environmental invertebrates and diseases.

Successful invasive species tend to have broad ecological tolerances, effective reproductive and dispersal mechanisms, competitive ability superior to that of natives in the original or modified system, and the capability of altering the site by significantly changing resource ability and/or disturbance regimes.[283] Only when invasions are caught early will the chance of eradication remain high. In addition to saving money, early detection and rapid response efforts minimize ecological damage by preventing habitat fragmentation and ecosystem degradation associated with large or widespread invasive species populations and related management activities.

Surveillance and monitoring activities are essential to collect the information needed to underpin rapid response actions and implement measures to prevent newly- introduced invasive species establishing (See Appendix E). The difference between surveillance and monitoring activities can be summarised as follows:

- surveillance is an activity aimed at identifying alien species new to a country, and as such is a pivotal element of prevention.[284]
- monitoring programmes are useful to acquire a better understanding of the ecology, distribution, patterns of spread and response to management of an invasive species, and as such can strengthen the capacity to predict the consequences of invasive species introductions, and identify or assess the best management options if required.[285]

Dedicated surveillance programmes can be established at entry points (i.e. points of import) in the form of border controls and quarantine measures. Implementation such programmes can help prevent or minimise the risk of introducing alien species that are, or could become, invasive; or protect particularly vulnerable areas, such as islands. Surveillance programmes would be of limited efficacy if carried out on a local scale. As such, it is clearly important to for an **Australian invasive species surveillance system** to optimally use existing capacity; involve key societal sectors; and promote standardised procedures to collect, analyse and promptly circulate information on new incursions. Contrastingly, **monitoring programmes** can be designed for specific regions or species and are useful to provide critical information to support invasive species prevention, mitigation and restoration actions.

The Australian Government's *Agricultural Competitiveness White Paper* ('the White Paper') also highlights the importance of surveillance to form the basis of a strong biosecurity system to manage

[283] Rejmánek, M., & Richardson. D.M., 'What attributes make some plants more invasive?', *Ecology*, vol. 77, no. 6, 1996, pp. 1655-1661.

[284] Hester, S.M. & Cacho, O.J., 'The contribution of passive surveillance to invasive species management', *Biol. Invasions*, vol. 19, 2017, pp. 737–748. https://doi.org/10.1007/s10530-016-1362-4

[285] de Miliano, J., Woolnough, A., Reeves, A., & Shepherd, D., *Ecologically significant invasive species, a monitoring framework for natural resource management groups in Western Australia*, Department of Agriculture and Food, Western Australia, Perth, Bulletin 4779, 2010. https://researchlibrary.agric.wa.gov.au/bulletins/160/

invasive species.[286] Monitoring programmes may also provide a stronger scientific basis for decision-making and allocation of resources.[287, 288]

Here, we provide an example of how this could be done using an indicative invasive species (Khapra Beetle) as the target group and Australia as the importing/exporting region, with the rest of the world as global trade partners (Figure 7). The exotic Khapra beetle is a major global pest of storage grain, can reduce grain volume by 75%, [289] and if it breaches biosecurity efforts and establishes in Australia, will greatly impact livestock feed availability and potentially contaminate livestock.[290]

CISS has applied this approach for Asian-black spined toad, a priority exotic environmental biosecurity pest, with the development of new genetic and potential acoustic detection tools, and initial trials of cage traps to attract and catch Asian Black-Spined Toads have been completed in Southern Queensland, with monitoring now being extended to other areas of Queensland. Further monitoring will allow calibration of the trap (e.g. radius of attraction, probability of capture) and is a key step in evaluating trap sensitivity and designing an integrated surveillance system. The team is working with Australia's largest repository of community surveillance data, the *Atlas of Living Australia* (ALA) to develop a process to identify exotic vertebrates of concern within ALA's data streams. Work is in progress to determine where along the data capture process detections are made and how they should be reported to each jurisdiction involved.[291]

[286] Department of Agriculture, Water and Environment (DAWE), *Agricultural Competitiveness White Paper*, Commonwealth of Australia, 2014, https://www.agriculture.gov.au/sites/default/files/documents/ag-competitiveness-white-paper_0.pdf (accessed 17/08/2020).

[287] Holden, M.H., Nyrop, J.P. & Ellner, S.P. 'The economic benefit of time-varying surveillance effort for invasive species management', *Journal of Applied Ecology*.,vol. 53,no. 3, 2016, pp. 712-721. https://doi.org/10.1111/1365-2664.12617

[288] Bogich, T.L., Liebhold, A.M. & Shea, K., 'To sample or eradicate? A cost minimization model for monitoring and managing an invasive species', *Journal of Applied Ecology*, vol. 45, 2008, pp. 1134–1142. https://doi.org/10.1111/j.1365-2664.2008.01494.x

[289] Plant Health Australia, *Fact Sheet: Khapra beetle*, 2013, https://www.planthealthaustralia.com.au/wp-content/uploads/2013/01/Khapra-beetle-FS.pdf (accessed 17/08/2020).

[290] Australian Government, 'Khapra beetle (*Trogoderma granarium*)', *Department of Agriculture* [website], 4 November 2019, http://www.agriculture.gov.au/ pests-diseases-weeds/plant/khapra-beetle#how-to-identify-khapra-beetletrogoderma-granarium (accessed 17/08/2020).

[291] CISS 'Development of integrated passive and active surveillance tools and networks', *CISS* [website], 2017, https://invasives.com.au/research/development-integrated-passive-active-surveillance-tools-networks/ (accessed 3/10/2020).

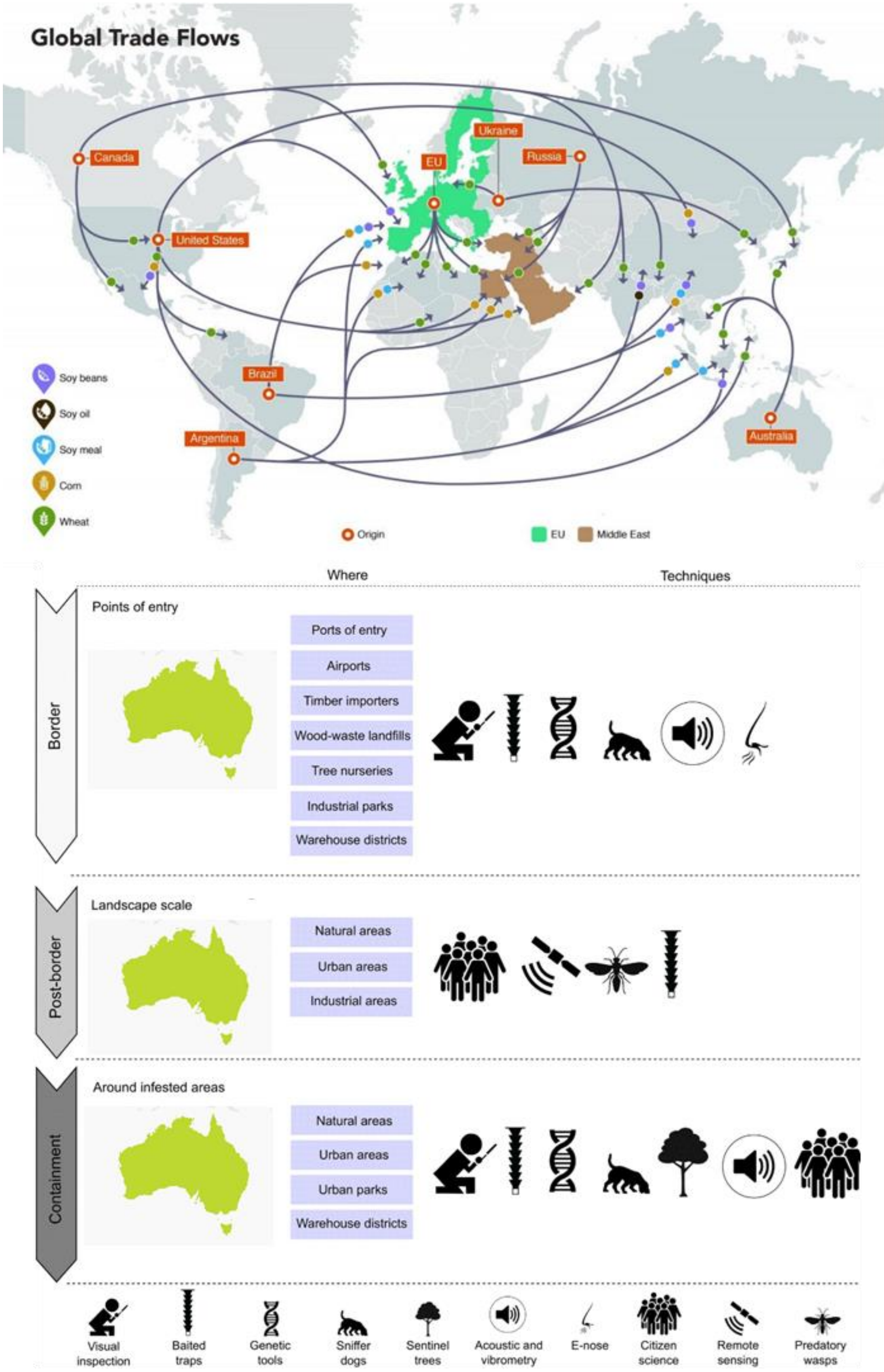

Figure 7. Example Biosecurity Technology Integration Model.

Example of how to integrate available technological advancements under the CISS developed platforms (together with traditional tools) into a comprehensive biosecurity surveillance program. A similar framework can be developed for other invasive species.

Source: Adapted from Poland, T.M. & Rassati, D., 'Improved biosecurity surveillance of non-native forest insects: a review of current methods', *J. Pest. Sci*., vol. 92, 2019, pp. 37–49. https://doi.org/10.1007/s10340-018-1004-y

8.1 IMPLICATIONS FOR VERTEBRATE PESTS

Despite recent advances, decades old broad-spectrum toxins and traplines are still the mainstay of vertebrate pest control.[292] 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 such as AI and IoT, big data handling, and testing at local scale as a platform for landscape-scale extrapolation.

Emerging technologies still requiring significant research and development include 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[293], to combine low-residue characteristics with selectivity and humaneness[294]. Semiochemical-based lures, when combined with effective delivery technologies, will provide controlled odour release and long life, factors that will help expand the utility of resetting toxin-delivery systems and traps.[295] 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; 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.[296] 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.[297]

8.2 IMPLICATIONS FOR WEEDS

Scouting for weeds is an important activity to assist weed management decision making and has been carried out by trained specialists through extensive and routine visual examination of the fields. Recent advancements in Unmanned Aircraft Systems (UAS)-based tools and geospatial information technology have created enormous applications for efficient and economical assessment of weed infestations as well as site-specific weed management.

The utilisation of UAS-based technologies for weed management applications is currently in its infancy, but this field has witnessed rapid growth in recent times in terms of aerial data acquisition and analysis. Challenges exist in UAS platform reliability, sensor capability and integration, image pre-

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

[293] Murphy, E. et al., 'A new toxin delivery device for stoats-results from a pilot field trial', *New Zealand Journal of Zoology*, vol. 45, no. 3, 2018, pp. 184-191. https://doi.org/10.1080/03014223.2018.1461118

[294] Eason, C. T. et al., 'Trends in the development of mammalian pest control technology in New Zealand', *New Zealand Journal of Zoology*, vol. 44, no. 4, 2017, pp. 1-38 https://doi.org/10.1080/03014223.2017.1337645

[295] Jackson, M., Linklater, W. & Keyzers, R., 'The development of semiochemical lures for invasive rats: an integrated chemical image and response-guided approach', *Proceedings of the 27th Vertebrate Pest Conference*, 2016, pp. 317-321. https://doi.org/10.5070/V427110327

[296] Horak, K., 'RNAi: Applications in Vertebrate Pest Management', *Trends in Biotechnology*, 2020, https://doi.org/10.1016/j.tibtech.2020.05.001 .

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

processing, quantitative assessment and prediction, final product development, and product delivery.[298]

Remote sensing can provide a convenient solution to largely replace ground-based manual scouting for weeds. Remote sensing provides precise and timely data collection, which helps in implementing short- and long-term strategies for crop management. Inclusion of remote sensing to an integrated weed management system can help with optimising herbicide use and reducing the risk of herbicide resistance evolution in weeds.[299] Satellite sensor technologies potentially combined with artificial neural networks are another alternative to study weed invasion.

Invasive plants with varying levels of genetic diversity can provide important models with which to study plant invasion success. DNA sequencing technologies provide precise and clear information related to the identity of invasive plant species, along with information on genetic diversity and phylogeographic history. New sequencing technologies are also likely to continue to allow greater resolution of genetic relationships among invasive plant populations, thus improving our understanding of mechanisms driving successful invasion.[300]

8.3 IMPLICATIONS FOR ENVIRONMENTAL INVERTEBRATES

Emerging DNA metabarcoding techniques could potentially revolutionise monitoring of invertebrates by providing the ability to characterise entire communities from a single, easily collected environmental sample.[301] Future improvements in DNA sequencing read lengths and reference database coverage should enable more confident sequence identifications, resulting in increased utility of DNA metabarcoding techniques. The advantages of DNA barcoding are that it allows for identification of species when morphological identification may offer only estimates of higher taxonomic levels or no estimate at all[302], it recognises cryptogenic species[303], and it is rapid and cost-effective[304]. DNA identification has been applied to a wide variety of taxa including Copepoda[305], Lepidoptera[306], Culicidae[307] and Araneae[308].

Recent CRSPR/Cas9 research has demonstrated the possibility of using gene drive modified organisms in the conservation of threatened and endangered species and in the eradication of insect-borne infectious diseases.[309] Gene drives could potentially play a significant role in the management

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298 Vijay, S. et al., 'Chapter Three - Unmanned aircraft systems for precision weed detection and management: Prospects and challenges', *Advances in Agronomy*, vol. 159, 2020, pp. 93-134. https://doi.org/10.1016/bs.agron.2019.08.004.

299 Bolch E.A. et al., 'Remote detection of invasive alien species', in Cavender-Bares, J., Gamon J., Townsend, P., (eds), *Remote Sensing of Plant Biodiversity*, Springer, 2020. https://doi.org/10.1007/978-3-030-33157-3_12

300 Razia, S. et al., 'Understanding invasion history and predicting invasive niches using genetic sequencing technology in Australia: case studies from *Cucurbitaceae* and *Boraginaceae*', *Conservation Physiology*, vol. 4, no. 1, 2016, cow030, https://doi.org/10.1093/conphys/cow030

301 Watts, C. et al., 'DNA metabarcoding as a tool for invertebrate community monitoring: a case study comparison with conventional techniques', *Austral. Entomology*, vol. 58, 2019, pp. 675–686. https://doi.org/10.1111/aen.12384.

302 Darling, J.A. & Blum, M.J., 'DNA-based methods for monitoring invasive species: a review and prospectus', *Biol. Invasions*, vol. 9, 2007, pp. 751–765.

303 Geller, J.B., Darling, J.A. & Carlton, J.T., 'Genetic perspectives on marine biological invasions', *Annu. Rev. Mar. Sci.*, vol. 2, 2010, pp. 367–393. https://doi.org/10.1146/annurev.marine.010908.163745

304 Wong, E. H. K. & Hanner, R.H., 'DNA barcoding detects market substitution in North American seafood', *Food Res. Int*., vol. 41, no. 8, 2008, pp. 828–837.

305 Bucklin, A. et al, 'Molecular systematic and phylogenetic assessment of 34 calanoid copepod species of the *Calanidae* and *Clausocalanidae*', *Mar. Biol*., vol. 142, 2003, pp. 333–343. https://doi.org/10.1007/s00227-002-0943-1

306 Janzen, D. H, et al., 'Wedding biodiversity inventory of a large complex Lepidoptera fauna with DNA barcoding',. *Philos. Trans. R. Soc. Lond. B. Biol. Sci*., vol. 360, 2005, pp. 1835–1845. https://dx.doi.org/10.1098%2Frstb.2005.1715

307 Shouche, J.S. & Patole, M.S., 'Sequence analysis of mitochondrial 16S ribosomal RNA gene fragment from seven mosquito species', *J. Biosci*., vol. 25, 2000, pp. 361–366.

308 Barrett, R. D. H. & Hebert, P.D. N.,'Identifying spiders through DNA barcodes', *Can. J. Zool*., vol. 83, 2005, pp. 481–491.

309 Collins, J. P.,'Gene drives in our future: challenges of and opportunities for using a self-sustaining technology in pest and vector management', *BMC Proceedings,* vol. *12, no.* 9, 2018. https://doi.org/10.1186/s12919-018-0110-4

of invertebrate species.[310] For example, Honeycreepers and other endemic birds in Hawaii have evolved in the absence of avian malaria and, consequently, are particularly susceptible to the invasive malaria parasite *Plasmodium relictum*.[311] An eradication drive targeting mosquito populations could protect endemic birds.[312]

An alternative to eradication drives includes the introduction of cargo genes that code for antibodies preventing the reproduction and transmission of the parasites.[313] Note that strategies alternative to gene drives based on the sterilisation of females with irradiation (sterile insect technique) or using the bacteria *Wolbachia* (incompatible insect technique) are currently being developed in different mosquito species.[314, 315] An alternative approach conducted by the company Oxitec uses the 'release of insects carrying a dominant lethal genetic system' (RIDL). This method has been conducted to combat mosquitoes, the vectors of pathogens of many human diseases.

The specificity of RNAi makes it a desirable tool for insect pest management, reducing the chances of spreading its toxicity to other nontarget organisms in the wild. The most common methods used to deliver RNAi ingestion by insects via systemic endocytosis are microinjection and feeding. Feeding insects transgenic plants containing dsRNA has proven a useful method of pest control for crop protection against the western corn rootworm (*Diabrotica virgifera virgiera*)[316], and a dsRNA enriched diet is proven to be a successful pest control of the pea aphid *Acyrthosiphon pisum*, regardless of life stage[317]. However, RNAi via feeding can fail due to a low concentration of the dsRNA reaching the gut epithelium.[318, 319]

Machine learning techniques, and deep learning in particular, have been showing a remarkable ability to properly detect and classify pests, either in traps or natural images.[320] Based on data accumulated from intelligent traps, predictive analyses of invasive species attack can be made allowing better management.[321, 322]

E-noses are able to distinguish insects based on their chemical emissions and therefore could be used to detect the presence of a given non-native species inside shipping containers.
The main advantages of E-noses are that they allow for repeated non-destructive analyses, can be applied to bulk samples, and can detect both adult and larval damage even if symptoms are not visible.[323] Remote sensing instruments have been investigated as a potential post-border

[310] Collins, J. P., 2018.

[311] Lounibos, L.P., 'Invasions by insect vectors of human disease', *Annu. Rev. Entomol*., vol. 47, 2002, pp. 233–266. https://doi.org/10.1146/annurev.ento.47.091201.145206

[312] National Academies of Sciences, Engineering, and Medicine (NASEM), *Gene drives on the horizon: advancing science, navigating uncertainty, and aligning research with public values*, National Academies Press, Washington D.C., 2016. https://doi.org/10.17226/23405

[313] Gantz, V.M. & Bier, E., 'The dawn of active genetics', *BioEssays*, vol. 38, 2016, pp. 50–63. https://doi.org/10.1002/bies.201500102

[314] Lees, R.S. et al., 'Back to the future: the sterile insect technique against mosquito disease vectors', *Curr. Opin. Insect Sci.*, vol. 10, 2015, pp. 156–162. https://doi.org/10.1016/j.cois.2015.05.011

[315] Ritchie, S. A. et al., 'Mission accomplished? We need a guide to the 'post release'world of Wolbachia for Aedes-borne disease control', *Trends Parasitol*. vol. 34, no. 3, 2018, pp. 217–226. https://doi.org/10.1016/j.pt.2017.11.011

[316] Baum, J. A. et al., 'Control of coleopteran insect pests through RNA interference', *Nat. Biotechnol.,* vol. 25, 2007, pp. 1322–1326. https://doi.org/10.1038/nbt1359

[317] Mao, J., & Zeng, F., 'Feeding-based RNA interference of a gap gene is lethal to the pea aphid, *Acyrthosiphon pisum*', *PLoS One*, vol. 7, 2012, e48718. https://doi.org/10.1371/journal.pone.0048718

[318] Baum, J. A. et al., 2007.

[319] Mao, J., & Zeng, F., 2012.

[320] Barbedo, J.G.A., 'Detecting and classifying pests in crops using proximal Images and machine learning: A review', *AI 2020*, vol. 1, no. 2, 2020, pp. 312-328. https://doi.org/10.3390/ai1020021

[321] Fedor, P. et al., 'Artificial intelligence in pest insect monitoring', *Systematic Entomology*, vol 34,no. 2, 2009, pp. 398-400. https://doi.org/10.1111/j.1365-3113.2008.00461.x

[322] Future Farming, 'Tarvos monitors insects with computer vision and AI', *Future Farming* [website], 6 July 2019, https://www.futurefarming.com/Tools-data/Articles/2019/7/Tarvos-monitors-insects-with-computer-vision-and-AI-446605E/ (accessed 18/08/2020).

[323] Cellini, A. et al., 'Potential applications and limitations of electronic nose devices for plant disease diagnosis', *Sensors*, vol. 17, no. 11, 2017, pp. 2596. https://dx.doi.org/10.3390%2Fs17112596

surveillance tool. Detection of rapid changes in spectral, structural, and temporal characteristics of vegetation may indicate the presence of invasive invertebrate species.[324]

Cost-effective surveillance strategies are needed for efficient responses to biological invasions and must account for the trade-offs between surveillance effort and management costs. Greater surveillance with advanced technologies described above, better monitoring of the established pests and active community engagement, will enhance invasive species management in Australia in the future.

8.4 CONCLUDING REMARKS

Biosecurity is fundamental for safeguarding our valuable agricultural resources against the threat and impacts of pests, weeds and diseases (pests). CISS has demonstrably focused on emerging technologies and management practices that have national and international application and effectively delivered solutions through a partnership model. Our 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 pest species and limit impacts on both agricultural production and our rural and urban landscapes.

[324] Asner, G.P. et al., 'Remote sensing of native and invasive species in Hawaiian forests', *Remote Sens. Environ.*, vol. 112, 2008, pp. 1912–1926. https://doi.org/10.1016/j.rse.2007.02.043

APPENDIX A PUBLISHED DATA ON GLOBAL MEGATRENDS

Australian agriculture has undergone considerable change over the last few decades. Due to sustained productivity growth, agricultural output has more than doubled in this period. Nevertheless, with the even faster growth of the services sector, agriculture's relative share of the economy has declined. At the same time, there have been marked changes in the makeup of the sector, driven by a variety of domestic and international forces. Some key factors driving change in the sector include globalisation, trade liberalisation, changing consumer tastes, technological advances and innovation, and environmental constraints. The unrelenting decline in farmers' terms of trade (that is, the ratio of prices received for farm products compared to prices paid for farm inputs) has also been an important pressure for change.

In recent years a range of forward-looking analyses have been undertaken to describe the major forces shaping the future, to categorise these into sets of 'megatrends', and in some cases to integrate them to project potential alternative future scenarios. The global megatrends considered most likely to have a profound impact on Australia's food and agriculture sector were identified by CSIRO and RIRDC in the 2015 report *Rural Industry Future: Megatrends impacting Australian agriculture over the coming twenty years* as shown in Figure 8.[325]

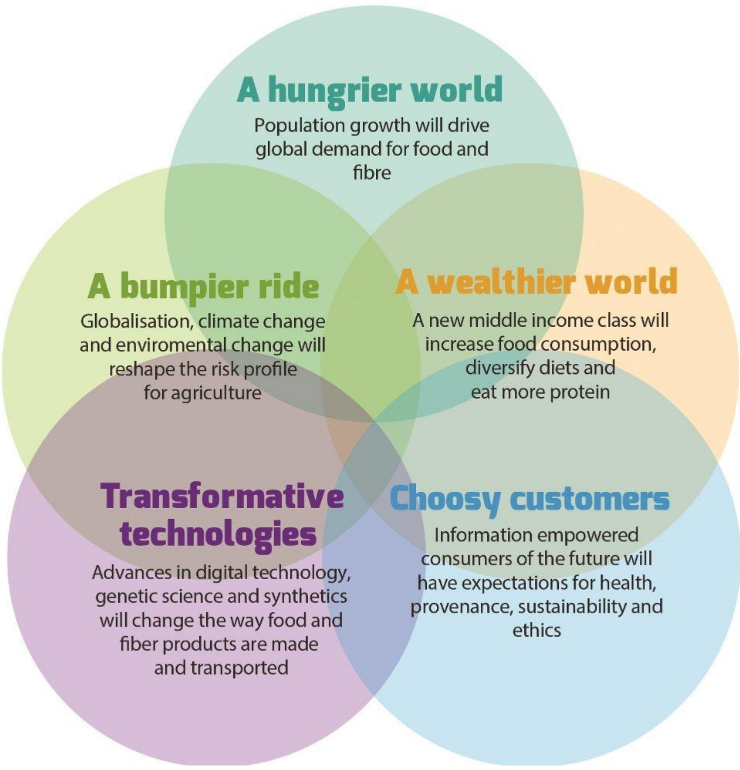

Figure 8. Megatrends impacting Australian rural industries.
Source: Hajkowicz, S. & Eady, S., *Rural Industry Futures: Megatrends impacting Australian agriculture over the coming twenty years*, CSIRO and RIRDC, 2015.

The report noted that the megatrends identified covered both domestic and global drivers of change because Australian agriculture is an export oriented industry which presently sells approximately two thirds of its produce offshore. While domestic market requirements will necessarily remain an important priority for Australian farm production, there are faster-growing and more-rapidly approaching opportunities in emerging markets. This is occurring especially in Asia, where food and

[325] Hajkowicz, S. & Eady, S., Rural Industry Futures: Megatrends impacting Australian agriculture over the coming twenty years, CSIRO and RIRDC, 2015.

fibre demand has doubled or trebled in recent years and are set for continued growth with increasing population and a rising middle class demographic.

Several themes were identified in the report which represent key opportunities and/or challenges for Australian rural industries:

- Continued productivity gains (including labour productivity) are required in agriculture to deal with competitive terms of trade and a labour force that is declining through ageing.

- Australian agriculture is predominantly export-oriented which means the sector benefits from, and is heavily reliant on, the market demand and consumer preferences of these global markets.

- Variability in agricultural profitability has significantly increased due to climate variability, volatile exchange rates and fluctuations in market demand.

- The trend of production consolidation to fewer, larger farms continues in response to the need for improved competitiveness. The family farm remains the most common ownership structure, abiet these are increasingly becoming corporations and it increasingly faces pressure to grow and to maintain efficiency.

- Growth and diversification of exports is required in response to structural change in emerging economies – for example, an increased middle-income class, especially in Asia, driving stronger demand for a more diverse range of products whilst global commodity production becomes increasingly competitive.

- Access to quality production resources (arable land, reliable water, cost efficient nutrition and pesticides, elite adapted seed and germplasm) and proximity to markets remain major factors in planning for increased production capacity.[326]

A year before in 2014, CSIRO published yet another report on megatrends[327] but with a primary focus on biosecurity megatrends. This report identified five biosecurity megatrends (*An Appetite for Change; The Urban Mindset; On the Move; A Diversity Dilemma; and The Efficiency Era*) that all point towards a shift in the types of biosecurity risks we are likely to face in the future and the way that these risks will need to be managed. The report importantly mentions that these megatrends relating to agricultural expansion and intensification, urbanisation and changing consumer expectations. Global trade and travel, biodiversity pressures, and declining resources could lead to a future where existing processes and practices relating to biosecurity are not sufficient, and continuous improvement needs to be made. Importantly, the megatrends should not be considered in isolation as they are all interrelated and the interactions of the different megatrends have the potential to lead to biosecurity mega shocks.

Besides the above mentioned reports, EY in 2015[328] in has identified six broader megatrends that will shape the decades to come. These are: digital future; entrepreneurship rising; global marketplace; urban world; resourceful planet; and health reimagined (Figure 9).

[326] Hajkowicz, S. & Eady, S., Rural Industry Futures: Megatrends impacting Australian agriculture over the coming twenty years, CSIRO and RIRDC, 2015.

[327] M. Simpson & V. Srinivasan, *Australia's Biosecurity Future: Preparing for future biological challenges*, CSIRO, 2014, https://publications.csiro.au/rpr/download?pid=csiro:EP146693&dsid=DS5 (accessed 03/10/2020).

[328] EY, *Megatrends 2015: Making sense of a world in motion*, EY, 2015. https://www.ey.com/Publication/vwLUAssets/ey-megatrends-report-2015/$FILE/ey-megatrends-report-2015.pdf (accessed 03/10/2020).

Figure 9. Global Megatrends as identified by EY.

Source: EYGM Ltd, *Megatrends 2015: Making sense of a world in motion*, EYGM Ltd, 2015.

The potential impacts of the megatrends within the food and agribusiness sector were highlighted further in a recent report by Cole et al (2018).[329] and also is highly consistent with both of the CSIRO/RIRDC and EY reports mentioned previously (Figure 10).

[329] M. B. Cole, M. A. Augustin, M.J. Robertson & J.M. Manners, 'The science of food security', *NPJ Science of Food*, vol. 2, no. 14, 2018. http://doi.org/ 10.1038/s41538-018-0021-9

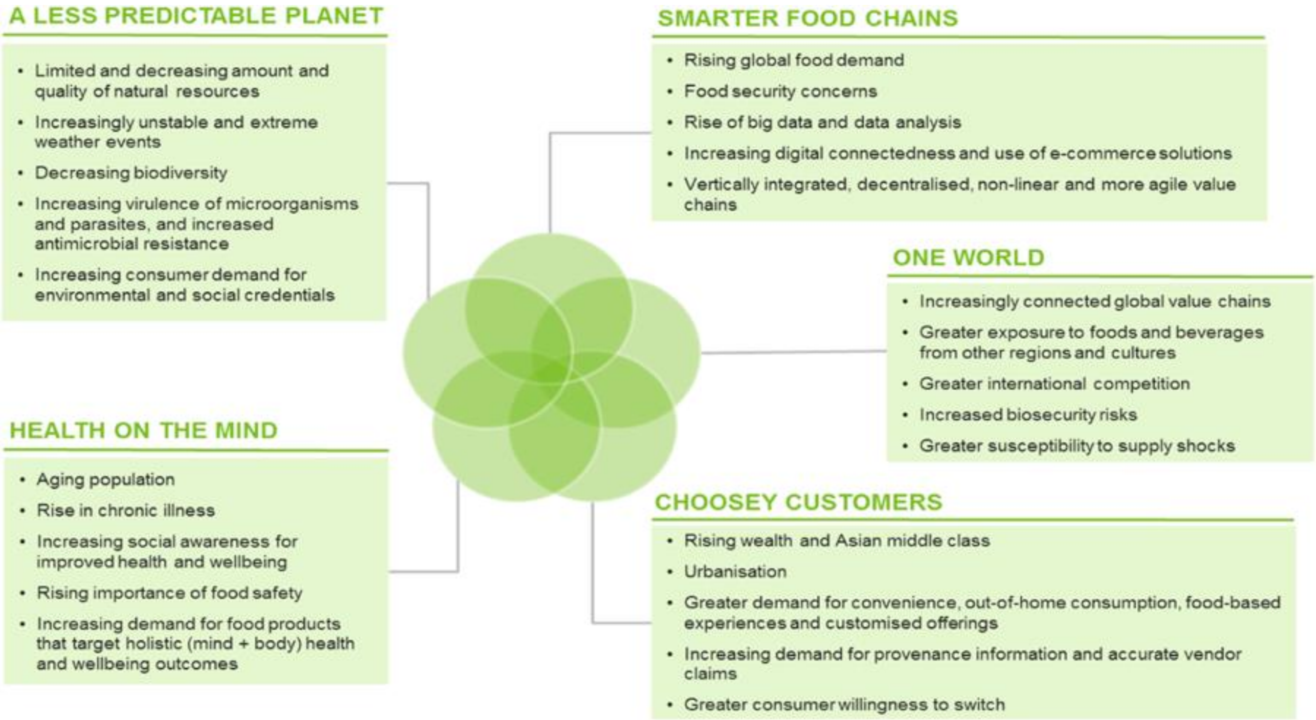

Figure 10. Key drivers and potential impacts arising from global megatrends in Food and Agriculture

Source: Adapted from Hajkowicz and Eady, 2015 [330] in Cole et al 2018 ; CSIRO Futures, 2017 [331]

Notably, a couple of years ago the National Farmers' Federation unveiled their roadmap for 2030, identifying opportunities or threats associated with them offering a vision of transforming the Australian agriculture sector into a 100 billion dollar industry (Figure 11).[332]

[330] Hajkowicz, S. & Eady, S., Rural Industry Futures: Megatrends impacting Australian agriculture over the coming twenty years, CSIRO and RIRDC, 2015.

[331] CSIRO Futures, Food and Agribusiness: A Roadmap for unlocking value-adding growth opportunities for Australia, Australia, CSIRO, 2017.

[332] National Farmers' Federation (NFF), *Road Map 2030: Australian Agriculture's Plan for a $100 Billion Industry*, NFF, 2018, https://nff.org.au/wp-content/uploads/2020/02/NFF_Roadmap_2030_FINAL.pdf (accessed 03/10/2020).

2030 Megatrends

Driver	Outlook	Assessment
Unprecedented demand	Burgeoning global populations and incomes – particularly on our Asian doorstep – will fuel demand for food and fibre in years to come. Improved market access will position Australia to service that demand, amplifying our geographic advantage.	Strength
Heightened expectations	Environmental, health, and welfare considerations will increasingly sway purchasing decisions. Meeting these expectations presents opportunities to build on our competitive advantage. It also increases reputational risks if expectations are not met.	Opportunity / Weakness
Disruptive technology	Digital and genetic technologies promise to unlock new waves of productivity growth across the sector. Automation will continue to improve quality of life for farmers, while reshaping the sector's skills needs.	Opportunity
Responding to climate change	Climate change will play a major role in Australian agriculture's next decade, exacerbating climate risk while creating diverse new income opportunities. Australia's policy response can position us as a global leader in low-emissions agriculture. Done poorly, our policy response could saddle farm businesses with additional costs.	Opportunity / Threat
Consolidating communities	Without intervention, growth in Australia's major cities and regional centres will continue to outstrip that of our smaller towns. This will compound existing pressure on labour and services for farm businesses and families.	Weakness
Fierce new competition	Competition will intensify as developing nations modernise their farming practices and supply chains. Competition will also arrive from non-traditional sources, as alternative proteins stake out a larger portion of the market. Meanwhile, global forces threaten to disrupt the established rules of international trade.	Threat

Figure 11. SWOT analysis of impact of megatrends on Australian agriculture.

Source: National Farmers' Federation (NFF), *2030 Roadmap: Australian Agriculture's Plan for a $100 Billion Industry*, NFF, 2018. https://nff.org.au/wp-content/uploads/2020/02/NFF_Roadmap_2030_FINAL.pdf

Due to Australia's vast geography and associated range of climatic conditions, impacts of global megatrends will vary between localities, depending on the unique characteristics of each region. Global megatrends are not short-term issues and are anticipated to have relevance for decades to come,[333] shaping the role of government policy, environmental, social and economic outcomes. The opportunity exists to establish Australia's role in a world that will need to feed an estimated population in excess of 9 billion by 2050 with diminishing natural resources, whilst ensuring the health of people and the planet (Figure 12).

[333] KPMG, *Future State 2030*, KPMG, 2013, p.6, https://assets.kpmg/content/dam/kpmg/pdf/2014/02/future-state-2030-v3.pdf (accessed 03/10/2020).

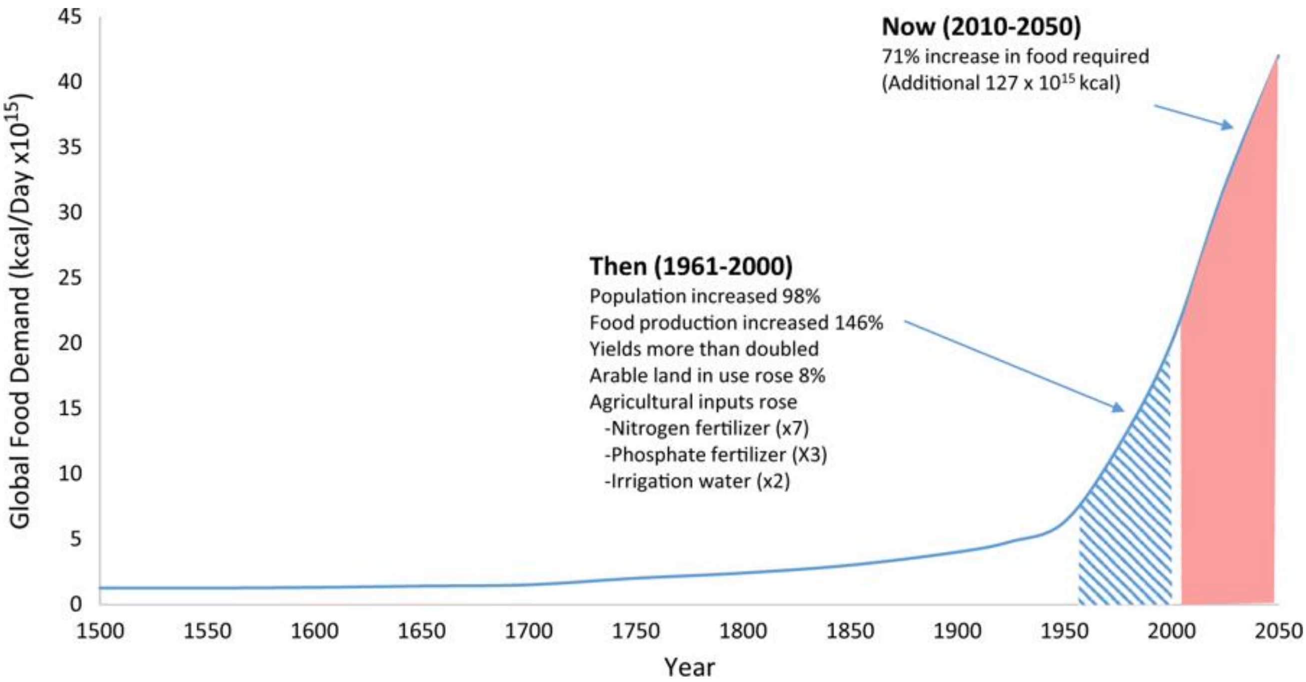

Figure 12. Framing the food security challenge.

Source: M. B. Cole, M. A. Augustin, M.J. Robertson & J.M. Manners, *NPJ Sci Food*, vol. 2, no. 14, 2018, Fig. 1 (Adapted from Keating, B.A. et al., 2014[334]; Keating, B.A. & Carberry, P.S., 2010[335]).

A recent report by Spiegare Pty Ltd, together with Animal Health Australia, on the biosecurity implications of megatrends on agriculture and livestock sector, also has highlighted several issues that needs to be addressed by Australia, for it to remain competitive and sustainable.[336] The key trends that are impacting the future of the Australian livestock sectors include:

- Climate change megatrends are re-shaping terrestrial and aquatic animal production systems. The decline in ecosystem services (such as water quality and availability, soil health and biodiversity) is causing changes in the geographical ranges of animal and plant diseases, insect vectors and feral animal hosts which is increasing disease risk and is stretching surveillance capability and capacity.

- Consumer megatrends are creating increased global demand for meat as well as alternative, more sustainable choices for protein and fibre. Alternative products from plant and bio-industrial processes will likely coexist with traditional products for the foreseeable future, so there are great opportunities for synergies. Citizen-science and the rapid social dissemination

[334] Keating, B. A. et al.,' Food wedges: framing the global food demand and supply towards 2050', *Glob. Food Sec*. vol. 3, 2014, pp., 125–132. http://dx.doi.org/10.1016/j.gfs.2014.08.004

[335] Keating, B. A. & Carberry, P. S., 'Sustainable production, food security and supply chain implications', in Martindale, W. (ed.), *Delivering Food Security through Supply Chain Led Innovations, 7-9 September 2010*, *Asp. Appl. Biol*., vol. 102, 2010, pp. 7–20. http://hdl.handle.net/102.100.100/107552?index=1

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

of information (including misinformation and disinformation) by individuals, groups and communities will also impact animal production.

- Technology megatrends offer extensive opportunities to support the sustained prosperity of livestock industries. Innovative tools for characterising new (previously unknown) diseases, or variants of existing diseases (including antibiotic-resistant microbes), should enable our growing 'omics' knowledge to predict the biology, host range and pathogenicity of new pathogens before they emerge and spread, allowing us to become increasingly proactive, rather than being reactive. Adoption of new technologies in biosensors, autonomous surveillance and diagnostics, and big data analysis will greatly improve biosecurity preparedness and response. Issues such as legislation in data protection and ownership, privacy, Freedom of Information and Right-to- Know in the face of accelerating data generation and predictive capacity will need to be considered.

- Changes in government resourcing and shifts to user-pay systems exacerbates the need to achieve improvements in resource use efficiency.

APPENDIX B CASE STUDY[337]

Box 1 Change in trade and patterns and exposure to biosecurity risk

The number of passengers, shipping and containerised cargo arrivals in Australia is forecast to increase by more than 70 per cent by 2025 (DIRD 2014). The possible effect of this increase on biosecurity risk to Australia, and its management by the Australian Government agriculture department, was explored using the department's Risk Return Resource Allocation (RRRA) model.

Using the RRRA model, projected volume increases to 2025 for four entry pathways (responsible for around half of the residual biosecurity risk to Australia) were examined: air and sea passengers; commercial vessels; sea containers (external surfaces only); and timber (bulk timber and wooden manufactured articles). Trade data and costs (Australian Government only) for 2014–15 were used as a baseline for three possible 2025 scenarios to manage biosecurity risks associated with the projected volume increases at the border (the analysis assumed no other adjustments, pre- or post-border, are made to manage risk):

- **Scenario 1 (Fixed investment):** Border clearance costs are maintained at 2014–15 levels.
- **Scenario 2 (Fixed intervention rate):** Border clearance processes adjust to changing volume (document processing and intervention rates).
- **Scenario 3 (Fixed residual risk):** Border clearance processes (intervention rates and effort) are increased in an attempt to maintain residual risk at the 2014–15 levels.

In 2014–15, around $90 million was spent managing biosecurity risk for the four pathways. The RRRA model calculated this investment to benefit Australia by $2.4 billion in avoided long-term losses[1] to agricultural industries, with $1.7 billion in residual biosecurity risk[2].

The analysis showed that, while increasing the investment in biosecurity interventions at the border does provide a benefit, it would not be sufficient to keep residual biosecurity risk at the 2014–15 level of $1.7 billion. Even almost tripling investment in interventions to $250 million (scenario 3), while providing an estimated benefit of $4.7 billion, only manages to reduce the residual biosecurity risk to $2.1 billion. The residual risk under scenario 2 was higher at $2.9 billion, with a lower estimated benefit of $3.8 billion. This highlights the importance of seeking innovative approaches, pre-border and post-border as well as at the border, to biosecurity risk management; simply increasing funding is not a 'silver bullet'.

This finding is reinforced by the diminishing return on investment (ROI) for the four pathways in scenarios 2 and 3. In comparison to the current (2014–15) ROI (27:1), the marginal ROI[3] on the additional investment is less than half under scenario 2 (12:1), and about one-quarter under scenario 3 (7:1). The overall ROI is also substantially reduced under scenario 3, dropping from 27:1 to 19:1.

1. Avoided long-term loss is the estimated reduction in exposure to biosecurity risk as a result of having biosecurity controls in place; 2. Residual biosecurity risk is what remains with biosecurity controls in place. [The sum of 1. & 2. is the biosecurity risk if no controls were in place]; and 3. Marginal ROI is the return on the additional investment needed to maintain current policy settings for border interventions (scenario 2) or to attempt to maintain residual risk at current levels (scenario 3).

Source: Australian Government Department of Agriculture and Water Resources.

[337] Craik, W., Palmer, D. & Sheldrake, R., Priorities for Australia's biosecurity system: An independent review of the capacity of the national biosecurity system and its underpinning intergovernmental agreement, Commonwealth of Australia, 2017, https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/biosecurity/partnerships/nbc/priorities-for-aus-bio-system.pdf (accessed 02/10/2020).

APPENDIX C DIGITAL SENSING[338]

	Spaceborne Surveys	Manned aerial Surveys	UAS Survey
Platforms	Satellite images are from GeoEye-1 (3/15), WorldView-1/2/3/4 (7/15), Quickbird-2 (3/15), and IKONOS satellites (1/15).	Aircraft used were mainly light manned helicopters (3/12) and fixed-wing aircraft (11/12). Surveyors of terrestrial mammals prefer using helicopters. Surveyors of animals in plains or marine environments prefer using fixed-wing aircraft. A long-period study used a combination of helicopters and fixed-wing airplanes.	UASs used include small fixed-wing UASs (11/18) and multicopters (9/18). Fixed-wing UASs are typically used to survey large or marine animals. Multicopter UASs are typically used to survey animals in uneven terrain and high-vegetation areas, as well as birds because of their superior vertical takeoff and landing capabilities and low noise.
Sensors	Panchromatic and multispectral images are the most widely used data (Two satellite remote sensing studies used panchromatic imagery, and the other thirteen studies used multispectral imagery). Pansharpening techniques were used to merge high-resolution panchromatic and lower-resolution multispectral imagery to create a single high-resolution color image to increase the differentiation between target objects and background.	Real-time surveys do not need imaging sensors. Photographic surveys used still RGB images, video, and infrared thermography to detect wild animals.	RGB images are suitable for detecting wild animals living in open lands or marine environments. Thermal infrared cameras are primarily used for detecting wild animals living in forests and other high-vegetation areas. Radio-tracking devices have been used on UASs in recent years to study the behavior of small animals.
Resolution	Up to 0.31 m resolution in the panchromatic band (WorldView-3 and -4) Up to 1.2 m in the multispectral band (WorldView-3 and -4)	Up to 2.5 cm (RGB imagery)	Up to 2 mm resolution (RGB imagery)
Coverage	Regional to global scales	Has been used for regular and geographically comprehensive animal monitoring on regional scales. Sampling distances were up to 12,800 km, with an area of approximately 6000 km^2.	No more than 50 km^2. Most survey areas were <2 km^2. The minimum survey area was only 4 × 4 m.
Cost	Relatively low (the price of 0.5 m spatial resolution satellite imagery ranges from USD $14–27.5 per km^2 depending on the spectral resolution, order area and data age).	Expensive to implement for small study areas because of the cost of the aircraft, operator, and fuel.	Medium Has been seen as a safer and low-budget alternative to manned aircraft.
Surveyed species	It is possible only to directly identify large-sized (≥0.6 m) individual animals from existing VHR commercial satellite imagery, such as wildebeests, zebras, polar bears, albatrosses, southern right whales, and Weddell seals.	The real-time survey method has long been used to survey terrestrial and marine animals with potentially low abundances in remote or large areas. Manned aerial imagery allows directly discern smaller (<0.6 m) animals, such as birds, sea turtles, and fish; large animals that are difficult to distinguish from the background at the species level, such as roe deer and red deer; and some animals with a significant temperature difference from the background environment, such as Pacific walruses.	UASs allow surveying of smaller animals, as well as their behaviors, such as butterfly species, Bicknell's and Swainson's thrushes, noisy miners, and iguanas. Most applications of UASs focus on assessing the possibilities of species detection in a small geographic area.
Methodology	Direct visual recognition and Automatic and semiautomatic detection using pixel-based and object-based methods	Direct visual recognition Automatic and semiautomatic detection using pixel-based and object-based methods and traditional machine learning.	Direct visual recognition Automatic and semiautomatic detection using pixel-based and object-based methods, traditional machine learning, and deep learning.
Pixel number of target species in imagery	2–6 pixels	Did not investigate, but similar to those for UAS imagery.	Most animals cover 22–79 pixels.
Accuracy	Automated and semiautomatic counts of animals from remote sensing imagery are reported to usually be highly correlated with manual counts when these algorithms were applied to small areas in relatively homogenous environments. The manual counts of animals derived from different remote sensing imagery and ground-based counts collected within a short time interval are also reported to be highly correlated. Remote sensing-based counts often underestimate populations because some animals are invisible to remote sensing imagery, especially those living in high-vegetation areas and aquatic environments, but high-resolution imagery increases the detection possibility.		

Note: The accuracy was determined through comparison with ground-based counts or manual counts.

Figure 13. Comparison of spaceborne, manned aerial, and unmanned aircraft system (UAS) surveys of wild animals.

[338] Wang, D., Shao, Q. & Yue, H., 'Surveying Wild Animals from Satellites, Manned Aircraft and Unmanned Aerial Systems (UASs): A Review', *Remote Sensing*, vol. 11, no. 11, 2019, 1308. https://doi.org/10.3390/rs11111308

Group	Species or Items Detected	Satellites	Resolution (in the Panchromatic Band)	Data Type
Terrestrial mammals	wildebeests (*Connochaetes gnou*), zebras (*Equus quagga*)	GeoEye-1	0.5 m	Multispectral imagery
	wildebeests (*Connochaetes gnou*), zebras (*Equus quagga*)	GeoEye-1	0.5 m	Panchromatic imagery
	polar bears (*Ursus maritimus*)	WorldView-2 and Quickbird	0.5 and 0.6 m, respectively	Multispectral imagery
	polar bears (*Ursus maritimus*)	GeoEye-1	0.5 m	Panchromatic imagery
	muskoxen (*Ovibus moschatus*)	WorldView-1 and WorldView-2	0.5 m	Multispectral imagery
Aquatic and amphibious animals	walruses and bowhead whales	GeoEye-1	0.5 m	panchromatic imagery
	southern right whales (*Eubalaena australis*)	WorldView-2	0.5 m	Multispectral imagery
	fin whales, southern right whales, and gray whales	WorldView-3	0.31 m	Multispectral imagery (Pansharpened)
	Weddell seals (*Leptonychotes weddellii*)	Quickbird-2 and WorldView-1	0.6 m	Multispectral imagery (Pansharpened)
	emperor penguins (*Aptenodytes fosteri*)	QuickBird	0.6 m	Multispectral imagery (Pansharpened)
	humpback whales (up to 10 m in length)	IKONOS	1 m	Multispectral imagery (Pansharpened)
	elephant seals (*Mirounga leonina*)	GeoEye-1	0.5 m	Multispectral imagery (Pansharpened)
	Weddell seals (*Leptonychotes weddellii*)	DigitalGlobe and GeoEye (specified satellites were not given)	0.6 m	Multispectral imagery (Pansharpened)
Flying organisms and insects	wandering albatross (*Diomedea exulans*) and northern royal albatross (*Diomedea sanfordi*)	WorldView-3	0.3 m	Multispectral imagery

Figure 14. Animal species detected using spaceborne imagery.

Group	Species or Items Detected	UAS Model (Type of UAS)	Sensor	Data Type	Surveyed Area (km²)	Flight Height (m)
Terrestrial mammals	roe deer (*Capreolus pygargus*)	Falcon-8 (fixed-wing, electric)	FLIR Tau640 thermal imaging camera	Thermal image	0.71	30–50
	elephants (*Loxodonta africana*)	Gatewing 100 (fixed-wing, electric)	Ricoh GR3 still camera	RGB image	13.79	100–600
	cows (*Bos taurus*)	Custom-made 750 mm carbon-folding Y6-multirotor (hexacopter, electric)	FLIR Tau 2 LWIR thermal imaging camera	Thermal image	<1.0 *	80–120
	koalas (*Phascolarctos cinerus*)	S800 EVO (hexacopter, electric)	Mobius RGB Camera +FLIR Tau 2-640 thermal imaging camera	RGB video + thermal video	0.01 *	20–60
	red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), and wild boar (*Sus scrofa*)	Skywalker X8 (fixed-wing, electric)	IRMOD v640 thermal imaging camera	Video	~1.0 *	149–150
Aquatic and amphibious animals	dugongs (*Dugong dugon*)	ScanEagle (fixed-wing, fuel)	Nikon D90 SLR camera + fixed video camera	RGB image+ RGB video	1.3	152–304
	American alligators (*Alligator mississippiensis*) and Florida manatees (*Trichechus manatus*)	1.5-m wingspan MLB FoldBat (fixed-wing, fuel)	Canon Elura 2	RGB video	1.3	100–150
	leopard seals (*Hydrurga leptonyx*)	APH-22 (hexacopter, electric)	Olympus E-P1	RGB image	<1.0 *	45
	humpback whales (*Megaptera novaeangliae*)	ScanEagle (fixed-wing, fuel)	Nikon D90 12 megapixel digital SLR camera	RGB image	35.2 *	732
	blacktip reef sharks (*Carcharhinus melanopterus*) and pink whiprays (*Himantura fai*)	DJI Phantom 2 (quadcopter, electric)	GoPro Hero 3	RGB video	0.0288	12
	gray seals (*Halichoerus grypus*)	senseFly eBee (fixed-wing, electric)	Canon S110+ FLIR Tau 2-640 thermal imaging camera	RGB image + thermal image	0.16 *	250
Flying organisms and insects	white ibises (*Eudocimus albus*)	1.5-m wingspan MLB FoldBat (fixed-wing, fuel)	Canon Elura 2	RGB video	1.3	100–150
	black-headed gulls (*Chroicocephalus ridibundus*)	Multiplex Twin Star II model (fixed-wing, electric)	Panasonic Lumix FT-1	RGB image	0.0558	30–40
	frigatebirds (*Fregata ariel*), crested terns (*Thalasseus bergii*), and royal penguins (*Eudyptes schlegeli*)	3D Robotics (octocopter, electric)	Canon EOS M	RGB image	<1.0 *	75
	gentoo penguins (*Pygoscelis papua*) and chinstrap penguins (*Pygoscelis antarctica*)	APH-22 (hexacopter, electric)	Olympus E-P1	RGB image	<1.0 *	45
	canvasbacks (*Aythya valisineria*), western/Clark's grebes (*Aechmophorus occidentalis/clarkii*), and double-crested cormorants (*Phalacrocorax auritus*)	Honeywell RQ-16 T-Hawk (hexacopter, fuel) and AeroVironment RQ-11A (fixed-wing, electric)	Canon PowerShot SX230, SX260, GoPro Hero3, and Canon PowerShot S100	RGB image	<1.0 *	45–76
	butterflies (*Libythea celtis*)	Phantom 2 Vision+ (quadcopter, electric)	GoPro Hero3	RGB image	0.000016	4
	Bicknell's and Swainson's thrushes (*C. ustulatus*)	Sky Hero Spyder X8 (octocopter, electric)	Radio transmitter (Avian NanoTag model NTQB-4-2, Lotek Wireless Inc., Newmarket, Ont., Canada)	Radio-tracking data	<1.0 *	50
	noisy miners (*Manorina Melanocephala*)	Unmentioned (hexacopter, electric)	Radio transmitter (Avian NanoTag model NTQB-4-2, Lotek Wireless Inc., Newmarket, Ont., Canada)	Radio-tracking data	<1.0 *	50

Figure 15. Detected animal species and employed unmanned aerial systems (UASs) determined via literature review

APPENDIX D CITIZEN SCIENCE[339]

Citizen science initiatives identified through our Scopus search. Code: "S", single species; "M", multiple species; * Statistic taken from the initiative's website (as of February 2019), ** statistic taken from the Global Biodiversity Information Facility website (https://www.gbif.org/), *** statistic taken from the iNaturalist website (https://www.inaturalist.org/).

	Alien plants	Native plants	Alien animals	Native animals	Number of observations	Home page	Data used in
EDDMapS	M		M		3,483,966*	https://www.eddmaps.org/	(Bois et al., 2011; Bradley et al., 2018; Cross et al., 2017; Falk et al., 2016)
Waarnemingen.be	M	M	M	M	32,393,358*	waarnemingen.be	Swinnen et al. (2018)
BugMap			S		n/a	https://www.facebook.com/pages/category/Community/Bugmap-1926843807640177/	Malek et al. (2018)
Pl@ntnet	M	M			709,411*	https://plantnet.org/en/	(Botella et al., 2018; Joly et al., 2016)
Yellowhammer dialects			S	S	9345*	http://yellowhammers.net	Pipek et al. (2018)
UK Ladybird Survey			S		48,510 (Roy et al., 2018)	http://www.ladybird-survey.org/	(Roy et al., 2018; Roy and Brown, 2015)
eBird			M	M	361,429,888**	https://ebird.org/home	Hobson et al. (2017)
iNaturalist	M	M	M	M	16,727,397*	https://www.inaturalist.org/home	(Ciceoi et al., 2017; Hobson et al., 2017; Mori et al., 2016; Spear et al., 2017)
iMapInvasives	M		M		44,943 (Cross et al., 2017)	https://www.imapinvasives.org/	Cross et al. (2017)
Invasoras.pt	M				15,245**	http://invasoras.pt/en/	Marchante et al. (2017)
Rasprostranenie Invasionnyh Vidov Rastenij ("RIVR")	S				18,347*	https://ib.komisc.ru/add/rivr/en/	Kuzivanova et al. (2017)
Invasive Mosquito Project			M	M	n/a	http://www.citizenscience.us/imp/index.php	Cohnstaedt et al. (2016)
Vildsvin og Vandløb ("Wild boar and Water Courses")			S		n/a	http://www.gis34.dk/map.aspx?caseid = 106	Jordt et al. (2016)
Southern African Bird Atlas Project			M	M	n/a	http://sabap2.adu.org.za/ (website down in February 2019)	Broms et al. (2016)
Ontario Reptile and Amphibian Atlas			M	M	17,101***	https://ontarionature.org/programs/citizen-science/reptile-amphibian-atlas/	Seburn (2015)
Mosquito Alert (formerly AtrapaelTigre.com)			S		4160*	http://www.mosquitoalert.com/en/	Kampen et al. (2015)
That's Invasive!	M		M		291 (Adriaens, 2015)	http://www.rinse-europe.eu/resources/smartphone-apps/	Adriaens (2015)
KORINA			M		7770 (Adriaens, 2015)	www.korina.info	Adriaens (2015)
Redmap			M		n/a	http://www.redmap.org.au/sightings/	Robinson et al. (2015)
Artportalen	M	M	M	M	32,000,000 (not all from citizens) (Preuss et al., 2014)	https://www.artportalen.se/	Preuss et al. (2014)
Project FeederWatch			M	M	n/a	https://feederwatch.org/	(Cooper et al., 2007; Koenig et al., 2013)
Invaders of Texas	M				21,826*	https://www.texasinvasives.org/invaders/	Gallo and Waitt (2011)
Project BudBurst	M	M			17,808*	https://budburst.org/	Wolkovich and Cleland (2011)
North American Breeding Bird Survey			M	M	n/a	https://www.pwrc.usgs.gov/bbs/index.cfm	Cooper et al. (2007)
Christmas Bird Count			M	M	n/a	https://www.audubon.org/conservation/science/christmas-bird-count	Cooper et al. (2007)
Invasive Pest Atlas of New England/Outsmart	M		M		72,165*	https://www.eddmaps.org/ipane/	(Bois et al., 2011; Cross et al., 2017; Starr et al., 2014)

Figure 16. Citizen Science initiatives.

Source: Johnson, B. 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', *Global Ecology and Conservation*, vol. 21, 2019, e00812. https://doi.org/10.1016/j.gecco.2019.e00812

[339] Johnson, B. 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', *Global Ecology and Conservation*, vol. 21, 2019, e00812. https://doi.org/10.1016/j.gecco.2019.e00812

APPENDIX E INTRODUCTION PATHWAYS OF INVASIVE SPECIES

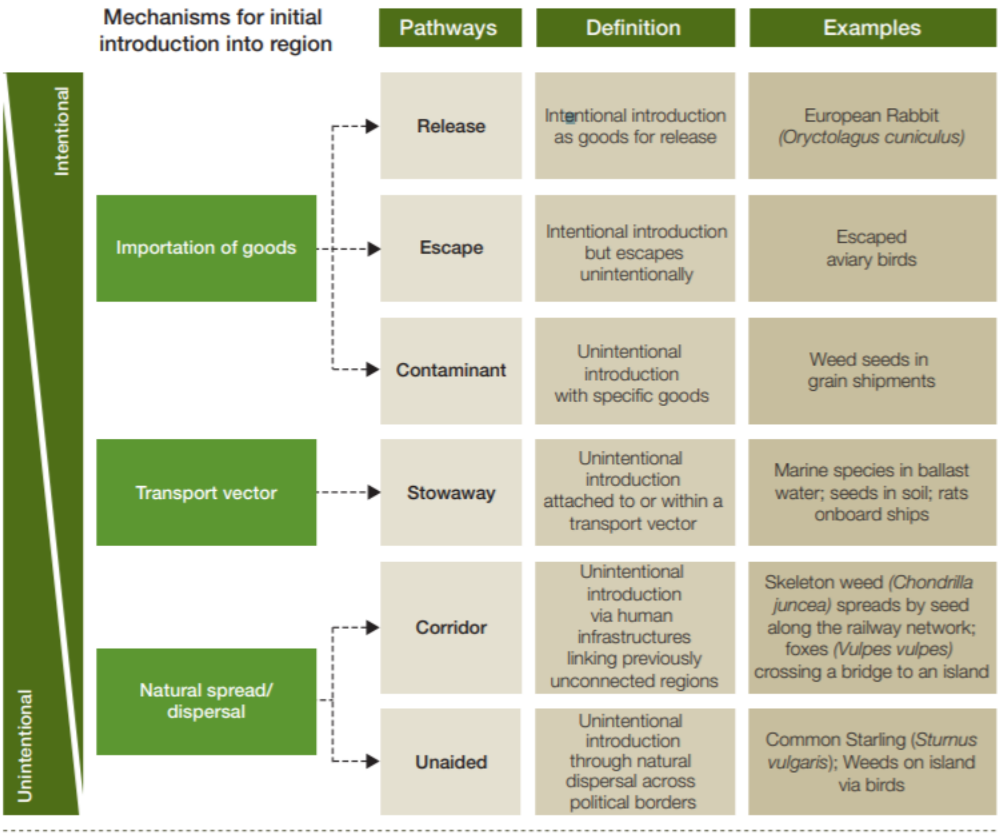

Figure 17. Introduction pathways.

Source: de Miliano, J., Woolnough, A., Reeves, A. & Shepherd, D., *Ecologically significant invasive species, a monitoring framework for natural resource management groups in Western Australia*, Bulletin 4779, Department of Agriculture and Food, Western Australia, Perth, 2010. https://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1164&context=bulletins (accessed 03/10/2020).

REPORT AUTHORS

Cameron Begley, Managing Director, Spiegare Pty Ltd

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 and 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 publicized 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 '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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