Final report

Dung beetle ecosystem engineers – enduring benefits for livestock producers via science and a new community partnership model

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Abstract

The Dung Beetle Ecosystem Engineers (DBEE) project aimed to improve the soil in grazing systems, reduce the spread of flies, pests and diseases, increase pasture health and reduce nutrient run-off into waterways through the introduction of new dung beetle species and the provision of management information to primary producers. Investigations were undertaken into how dung beetles can improve profitability and productivity for primary producers by:

- *rolling out a dung beetle services program to a network of producers and producer groups,*
- *improving access to information such as a dung beetle database, infield training and educational tools to improve delivery of well-adapted dung beetle species to Australian landholders,*
- *quantifying the benefits of dung beetles to encourage changes in farming practices to improve production and land management,*
- *importing new species of dung beetles to manage sheep and cattle dung, and encouraging producer-led rearing and distribution of recently imported dung beetle species.*

The legacy of the project following completion is planned to be an ongoing breeding supply and distribution chain for dung beetles and an understanding of the economic value of dung beetles across the Australian landscape.

DBEE was a Rural Research and Development for Profit (RRD4P) project and involved collaboration between MLA (the Grant recipient from the Commonwealth), universities (Charles Sturt, Western Australia, New England), Western Australian Department of Primary Industries and Regional Development, government research organisations (CSIRO, Landcare Research NZ), private companies (Dung Beetle Solutions International), natural resource management organisations (Warren Catchments Council) and farmer groups (Mingenew-Irwin Group).

Executive summary

The Dung Beetle Ecosystem Engineers (DBEE) project aimed to improve the soil in grazing systems, reduce the spread of flies, pests and diseases, increase pasture health and reduce nutrient run-off into waterways through the introduction of new dung beetle species and the provision of management information to primary producers. Investigations were undertaken into how dung beetles can improve profitability and productivity for primary producers by:

- rolling out a dung beetle services program to a network of producers and producer groups,
- improving access to information such as a dung beetle database, infield training and educational tools to improve delivery of well-adapted dung beetle species to Australian landholders,
- quantifying the benefits of dung beetles to encourage changes in farming practices to improve production and land management,
- importing new species of dung beetles to manage sheep and cattle dung, and encouraging producer-led rearing and distribution of recently imported dung beetle species.

The legacy of the project following completion is planned to be an ongoing breeding supply and distribution chain for dung beetles and a framework that provides producers across Australia, ongoing and relevant information to assist them maximise their on-farm benefit from dung beetles.

The DBEE project was a collaborative and multifaceted project that utilised a mixture of field monitoring, field and laboratory experimentation, quarantine, laboratory and field rearing of dung beetles, genetic analysis of imported dung beetle populations, and economic analysis. The experiments were undertaken across a wide range of landscapes, from Armidale in NSW around to Geraldton in WA, and managed by a diverse group of research partners. The DBEE project involved collaboration and financial support between MLA (the Grant recipient from the Commonwealth), universities (Charles Sturt, Western Australia, New England), Western Australian Department of Primary Industries and Regional Development, government research organisations (CSIRO, Landcare Research NZ), private companies (Dung Beetle Solutions International), natural resource management organisations (Warren Catchments Council) and farmer groups (Mingenew-Irwin Group).

Results/Key Findings

There are several clear key broader impacts that have resulted from the project that will contribute to the DBEE project legacy and continue to benefit Australian grazing livestock producers.

- Importation of four novel dung beetle species to fill the late winter-early spring activity gap in southern Australia (only three reared and released from quarantine). Another 14 species have been added to the Live Animal Import list for future importation.
- Enhanced producer awareness and capacity-building delivered through communications and extension activities.
- The curated data from the monitoring program is one of the largest databases of dung beetle presence and abundance in the world. This is important information for producers that will allow them to understand which dung beetle species are present/active when and where, to be able to tailor their land management practices to relevant species.

- The intensive field experiments conducted comprise the largest field experiment undertaken for the purpose of quantifying the benefits of dung beetles in the Australian context. Together with the economic model developed in the project, these findings demonstrate to farmers the benefits that dung beetles can provide. They will also encourage land managers to better actively manage their local beetle populations to improve on-farm productivity.
- The project has forged ongoing collaborations between land management organisations, commercial dung beetle providers and researchers that will continue to share knowledge and build capacity in dung beetle delivery.
- Mass-rearing facilities have been established at several sites across Australia and project partners have developed a much greater understanding of mass-rearing requirements for multiple dung beetle species.
- The DBEE project has led to increased demand for commercial dung beetle services and led to the establishment of community and private providers.

Recommendations

1. *Extension program:* In the regions that have not benefited from any of the projects and programs in the past decade, significant promotion of the ecosystem services and value of dung beetles to livestock producers is still required via a comprehensive extension program. There continue to be regions where very few producers understand the benefits that dung beetles can provide in pest management and the value they bring to a grazing system. Central and Northern Qld and the Northern regions of WA will require a coordinated program of extension based on locally developed adaption of the new communication and education materials. Ideally the new capacity developed in DBEE could be utilised to bridge some of these gaps.
2. *Geographic and seasonal gaps:* The benefits provided by dung beetles are assumed to be available to varying degrees in each locality that has dung beetles. Therefore, where there is a lack of dung beetles to provide those benefits, this represents an opportunity cost to farmers, the industry and the broader community. There are many geographical gaps across Australia where insufficient diversity and/or abundance of dung beetles means sub-optimal ecosystem service provision in that area. This can be divided into areas where:
   - there are species that are known to fit a gap but are not present due to a range of reasons such as geographical barriers to spread or harmful on-farm practices. Supplying a combination of different beetle species and the education required to ensure the action is successful is perhaps the lowest hanging fruit for any future funding into this area. There is already a combination of commercial and NGO groups active in this space, and although funding has been scarce, the concept has generally been boosted by the growing interest in ideas such as regenerative farming and soil carbon.
   - there are species that are present elsewhere in Australia that may be able to fit a gap, but they have not been tested/evaluated before. This is a more complex area and requires the assistance of technical experts.

    - Using a trap and relocate method, species of beetle that have adapted to regions outside previously known sightings could potentially be relocated to similar climatic and geographic regions.
    - New climate mapping of potential dung beetle distribution is needed to ensure the most successful outcomes from this relocation approach. Many of the tools available on dung beetle dispersal are based on climate mapping completed in early 2000s and updating these to reflect changes to our climate would provide an impetus for understanding where the beetles could establish.
- Areas where there are no species currently available in Australia that fit a particular gap. This is most likely because the gap falls into a region of unsuitable climate or soil types for currently available beetles. This ecosystem service gaps can only be filled by the careful selection, importation, rearing and establishment of a new species.
    - The cost and resources of successfully bringing in a new species are estimated to be in excess of $2m over five years. However, it should be noted that concurrently bringing in multiple species does not exponentially increase these costs. Therefore, the most efficient and successful model is likely to be the development of a pipeline program with committed funding over 8–10 years.
    - The funding of a continuing pipeline of new dung beetle species to fill the ecoservice gaps across the Australian farming landscape has been estimated to provide the largest potential benefit for the livestock industries and the authors also consider this the highest priority.

3. *Management of livestock and dung beetles:* Producers want specific and practical information packages on dung beetle management in relation to the use of animal health and pesticidal products. The key information providers on the best-practice use of pesticides in the livestock industries have limited available information on dung beetles, and in particular, how to include dung beetles into a holistic IPM strategy.

Benefits to Industry

In summary, the benefits brought by dung beetles to Australian farming systems has been estimated to be in excess of $620M per year, equating to a 6.1% increase in productivity. The monitoring program and broad contact and analysis made by this project suggests that this is only a small part of the potential that dung beetles could be providing if supported and managed from a farm, landscape and industry level. The extensive program of extension and communication throughout the project reached beyond the farms to also demonstrate to a broader community audience how the red meat industry utilises best practice to maximise productivity while protecting their farm environment.

This endeavour would not have been possible without the involvement and support of so many organisations and individuals. The partners in DBEE – Charles Sturt University, University of Western Australia, University of New England, CSIRO (Black Mountain), Dung Beetle Solutions International, Warren Catchment Council, Mingenew Irwin Group and Landcare Research New Zealand, WA Department of Primary Industries and Regional Development - acknowledges the support and research activities undertaken by collaborators - Farmlink, South West Prime Lamb Group, Southern Farming Systems, Mackillop Farm Management Group, CSIRO (Montpellier, France), Sidi Mohammed

Ben Adbellah University (Fez, Morocco); industry experts such as Greg Dalton from Creation Care and John Feehan from SoilCam; and the numerous dung beetle enthusiasts at land management groups across Australia who are advocates for these ecosystem warriors.

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1. Background

1.1 Project Rationale

Introduced dung beetles are a critical part of the Australian extensive animal production system, processing the dung of 27.5 million cattle, 68 million sheep and several million goats to ensure the nutrients are recycled, parasites and pests are reduced, and the broader environment is protected. The Dung Beetle Ecosystem Engineer (DBEE) program was designed to expand and enhance the activities and benefits of dung beetles in our southern farming systems (from Armidale, NSW around to Geraldton, WA), and educate farmers and the broader community of the critical roles dung beetles play.

Between 1965 and 1985 CSIRO released 43 exotic species to the mainland, of which 23 became established (Edwards, 2007). The Edwards (2007) report recommended an Australia wide sampling project to provide the latest distribution data for introduced dung beetle species. Over the decades since introductions were made there has been very little surveying undertaken on a large scale to understand where species have established, where they should be but aren't compared to the modelling and what major service gaps are prevalent. Surveying the seasonal and geographic distributions of exotic species has not been previously assessed, except in some localised studies. A wide survey across southern Australia would build on previous survey work in Queensland to provide a nation-wide survey of seasonal activity, which is an essential component of determining what species are missing and therefore what species should be introduced.

In 2012-2016 two spring-active dung beetles species (*Onthophagus vacca* French strain and *Bubas bubalus*) were imported as part of an MLA-CSIRO project. The beetles were reared by CSIRO and a small number of each species was released to high-care field nurseries. The expansion of the release of these species through continued rearing was the focus of initial rearing and field release efforts for DBEE researchers. The opportunity to expand the genetics of these introductions with the addition of the Moroccan strain of *O. vacca* could add to the adaptability and range of a potentially important spring active beetle.

Dung beetles are known to provide a range of environmental and social benefits but there is a lack of detail on the economic value of these benefits. Investigations were undertaken into how dung beetles improve profitability and productivity for primary producers and quantifying the benefits of dung beetles to encourage producers to take greater advantage of these benefits. By improving access to information such as a dung beetle database, and infield training packages with Landcare and Farming System Groups, an extensive education tool has been provided to the livestock grazing industry for continued use.

DBEE provided the opportunity to rebuild the capabilities and capacity of dung beetle research in Australia, given the still widely untapped potential dung beetles in extensive animal systems. With the imminent retirement of the previous generation of researchers this was also an opportunity to pass on practical knowledge as well as introduce new sciences and cross disciplinary skills (genetics, computer modelling, social science, economics)

The DBEE project was established under Round 3 of the Rural Research and Development for Profit program run by the then Department of Agriculture and Water Resources (DAWR). This large, multi-disciplinary project was overseen by Meat and Livestock Australia (MLA), with multiple partner institutions, including Charles Sturt University (CSU) as the lead, the University of Western Australia (UWA), the Commonwealth and Scientific Industrial Research Organisation (CSIRO), Dung Beetle

Solutions International (DBSI), the University of New England (UNE), Manaaki Whenua – Landcare Research New Zealand (LCNZ), Mingenew Irwin Group (MIG) and Warren Catchments Council (WCC). Several other organisations and farming systems groups were subcontracted to contribute to specific components of the project, including FarmLink, the MacKillop Farm Management Group, Southern Farming Systems (SFS), South West Prime Lamb Group and the Western Australian Department of Primary Industries and Regional Development (WA DPIRD). The project brought together a diverse range of expertise and many decades of experience and include specialists in dung beetle biology, insect and plant ecology, insect genetics, biological control and primary production.

2. Objectives

The broad objectives of the RRD4P DBEE project were to implement and deliver:

- National-level regionally specific dung beetle services to farmers to be rolled out under the national Landcare program.
- A publicly available national to regional dung beetle distribution monitoring program and database to underwrite improved service delivery.
- Peer-reviewed quantification of the complex multiple dung beetle benefits and services from the paddock to nation.
- A selection, importation, release and distribution pipeline for existing and new dung beetles to fill scientifically justifiable benefit gaps.
- Program management, communication, evaluation and reporting to MLA.

More specifically, key goals of the project included:

Objective: Selection, importation, release, mass rearing and distribution of a pipeline of existing and key new dung beetles to Australia, to fill scientifically justified dung beetle service gaps, including dung beetles targeting, for the first time, sheep dung and associated flies and parasites.

Although there are nearly 500 species of native dung beetles in Australia, most are adapted to small, hard, dry, pelletised marsupial droppings and not to dealing with the large, moist deposits of cattle and horses. Until CSIRO introduced exotic dung beetles in the 1960s, the dung of these herbivores sat on the soil surface, sometimes for years, locking up organic matter, smothering pasture growth and polluting waterways.

It is estimated that another 25+ species are required to fill the geographic and seasonal gaps across the Australian grazing landscape. One of the gaps identified across southern Australia was associated with the absence of spring active beetles, and in this DBEE project three potential dung beetle species/strains were identified and imported to Australia for rearing and distribution. The identified species are known to feed and process a range of dung types including sheep dung.

During this project, CSIRO successfully imported four new species, three of which were successfully reared in quarantine and provided beetles for mass rearing activities. Due to project delays caused by COVID19, only one of the new species has been released to field nurseries. Two are currently in mass rearing in controlled environments with planned releases to field nurseries later in 2023 assuming success in the controlled environments.

Objective: National to regional dung beetle distribution and impact monitoring program. Compile all historic and new field data across at least 120 farm sites into a new National Dung Beetle Database and associated analytical tools to i) underwrite the service delivery element, and ii) allow scaled regional evaluation of the multiple national benefits.

From the first releases of dung beetles in Australia in the 1960's through to the most recent introductions in 2015, a network of researchers, state departments, farmers and Landcare groups have been distributing these beetles across our landscape. The various species have adapted and thrived in many environments; however, we are aware of many gaps (seasonally and geographically) when there is little to no beetle activity and dung sits unprocessed.

The DBEE was to undertake the largest dung beetle monitoring program ever recorded, with the goal of assessing at least 120 sites over a minimum 12-month period across southern Australia. The information generated from this process would drive the selection of current species for the distribution/redistribution into gaps and form part of the basis of understanding the scale of economic impact dung beetles have had across southern Australia.

The curated data from the monitoring program is one of the largest databases of dung beetle presence and abundance in the world. Utilising monitoring traps set for 24hrs, project partners, farming system groups or private landholders set traps at 420 sites. Beetles from a further 817 site samples were identified by project partners on a less frequent basis, including targeted evaluations of the impact of fire and flood on populations. The monitoring collaborators employed the smartphone app developed specifically for the DBEE project, MyDungBeetle Reporter or MyPestGuide Reporter to record all trapping and monitoring activities. Over the duration of the project almost 20,000 reports were made via these reporting apps. The data has been uploaded and preserved on the Atlas of Living Australia (ALA) website to ensure accessibility by future researchers and once fully uploaded will make up approx. 40% of the recorded dung beetle sightings on ALA. This is important information for producers that will allow them to understand which dung beetle species are present/active when and where to be able to tailor their land management practices to relevant species.

Objective: Field-based ecosystem service evaluation methodology development and implementation to develop methods and modules that allow all above-listed categories of benefits and sub-benefits to be measurable from the paddock to national scale.

While there is much research on the ecosystem services dung beetles provide, very few sources have measured and applied an economic value. DBEE research has, for the first time, quantified economic, environmental and social benefits provided by dung beetles. The project has developed ecosystem service evaluation methodologies and quantified at a landscape level a) pasture health improvements, b) multiple soil improvements, c) nutrient runoff reductions, d) reduced gut and fly parasite loads, e) multiple producer and public bushfly reductions, including historic beetle benefits.

To make informed decisions, producers and landholders need to be able to value the past, present and future potential impact of dung beetles on our farming systems and the environment.

The project estimated that across the southern third of the continent, dung beetles increased revenue from all livestock products by at least 6% and can increase pasture growth by 13.5%. A key benefit of dung beetles to Australian and New Zealand pastures is the approximate 50% reduction in dung on the soil surface, which reduces pasture fouling, making more pasture available to livestock.

Objective: Regional dung beetle service delivery to farmers via infield training and online educational packages, supporting farmer decisions on which beetles they need and where to source them, while simultaneously augmenting a national citizen science database based on species already present.

The project plan was focused on extensive evaluation of dung beetle monitoring sites through to the rearing and distribution of the newly imported species, generating an understanding of the benefits and roles of dung beetles in plant nutrition, soil health and integrated pest management. The ecosystem services provided by dung beetles were communicated across the farming community through both direct and peer-to-peer knowledge exchange.

Dung beetle monitoring data were reported on the mapping applications associated with the project website and the Atlas of Living Australia, an independent database managed by CSIRO, containing the sightings of Australian flora and fauna together with relevant geospatial data. Uploading the data from the 400+ sites monitored by the DBEE project ensured this information is readily accessible for researchers, producers and community stakeholders into the future.

The project has forged ongoing collaborations between land management organisations, commercial dung beetle providers and researchers that will continue to share knowledge and build capacity in dung beetle delivery. An estimated 60+ regional groups participated 143 stakeholder presentations and webinars, 42 field days and workshops for producer groups across WA, SA, VIC, Tasmania, NSW and ACT. 0ver the project lifetime, outreach extension, particularly those in NSW, Vic and SA, grew in popularity and recognition resulting in significant demand for the project supported outreach extension program. In 2018, the project conducted less than 10 organised outreach events whereas in 2022, the demand for events outweighed the ability to conduct and organise events.

3. Methodology

The DBEE project was a multifaceted and collaborative project that utilised a mixture of field monitoring, field and laboratory experimentation, quarantine, laboratory and field rearing of dung beetles, genetic analysis of imported dung beetle populations, and economic analysis. In terms of managing this complexity, the project developed Themes to group activities together and assigned a theme led to oversee the activities that were often across multiple institutions. These themes were:

3.1 Theme 1 - Program Management

Theme 1 focused on project management, including partner collaboration. Charles Sturt University Gulbali Institute was responsible for managing project contracts, project monitoring and evaluation and reporting on a timely basis. Project management was also overseen by a steering committee comprising of project partners.

The project has been managed utilising a number of tools, including the development of project action plan (activity plan or GANTT), monitoring and evaluation plan, risk management plan, and a governance structure (Steering Committee and Project Management Group). Steering Committee meetings were conducted on a quarterly basis with Project Management Group meeting each month. The project was required to complete an independent review mid-way through and on completion of the project.

3.2 Theme 2 - Beetle Rearing

Theme 2 focused initially on the rearing of the recently introduced dung beetle species *Onthophagus vacca* and *Bubas bubalus* before moving to the three novel species or strains imported as part of this project. The rearing of these species occurred alongside other species that are already established in some parts of Australia but have not yet reached their natural limits of distribution.

The Mass Rearing theme used methods that were based on those developed by CSIRO in earlier projects. Knowledge, practical advice and troubleshooting advice was actively shared among the personnel involved in the geographically dispersed mass rearing efforts. The George Bornemissza Mass Rearing Facility at CSU Wagga Wagga was the only location that was established de novo and this proved to be highly effective providing a transition for the beetles from ideal conditions in the laboratory to field conditions. The facility comprised a suite of laboratory facilities such as controlled environment chambers, work areas, walk-in freezer for storage of dung, as well as walk-in mesh houses and field nurseries. This mix of complementary facilities mirrored broadly the long-running successful infrastructure at CSIRO Canberra. Generally, the laboratory-based rearing in which environmental conditions could be manipulated proved to be most effective because it allowed rearing to take place year-round rather than being locked into normal seasonal conditions that allow only a single generation per year. In the case of *O. vacca* for example, laboratory work with the imported Moroccan strain allowed at least two generations per year by placing adults under ideal conditions (especially temperature) for breeding and the subsequent growth and development of progeny. The adults from such a round of rearing were then subjected to a 20-week-long protocol to simulate field-overwintering after which they were physiologically primed to breed again.

Refinements to rearing protocols were made over the course of the project by experimenting with differing treatments for environmental conditions including temperature, timing, rearing medium as well as being informed by a comprehensive review of the international technical literature. That review will be published as an open access article in the high impact (IF 6.6) journal *Entomologia Generalis* in early 2023.

The rearing success achieved at the mass rearing facilities was in part due to complementing in-house expertise with a comprehensive review of the international literary on dung beetle rearing and this review has been accepted for publication in E*ntomologia Generalis et Applicata* as "Rearing dung beetles (Coleoptera: Scarabaeidae): Identifying knowledge gaps and future challenges". A sister article in the same journal covered the subtopic of mites found in association with dung beetles: "Beyond phoresy: symbioses between dung beetles (Coleoptera: Scarabaeidae: Scarabaeinae) and mites (Acari)". The rearing team also conducted several experimental investigations to refine the method such as optimal type of sand for rearing medium, methods to free beetles of mites, and identification of fungi associated with beetles.

The mass rearing activities were essential to building up the number of beetles available for release into carefully selected climate matched sites and custodians. These beetles must be conditioned for the field to give them the best chance of survival which required a generation to be reared for a further year in the mesh houses or farm nurseries to introduce them to the local environment while still providing unlimited food (dung) and protecting them from predation. This is a critical step as large losses are generally experienced in beetles released directly from the lab (controlled temperatures and semi-sterile environments) to field sites.

The mass rearing activities in the DBEE project has allowed for the establishment of new dung beetle rearing facilities and capacity, while also building specific skills for researchers, technicians, and students involved.

Due to delays induced by COVID19 global lockdowns, two of the imported species are still in quarantine and mass rearing with plans to release the beetles and their progeny to selected partners in 2023.

3.3 Theme 3 - Beetle Distribution

Theme 3 focused on the distribution of introduced species *Onthophagus vacca* (French strain), *Bubas bubalus* and other exotic dung beetle species to over 100 new, relevant sites across southern Australia, with site-specific dung beetle management recommendations. In addition, the beetles released through rearing in theme 2 were established in at least 100 new, species-appropriate sites across southern Australia with site-specific dung beetle advice and training provided for producers. Utilising climate matching tools as well as local dung beetle specialists, suitable regions were identified. From within these regions, sites with ideal soil types and willing collaborators were selected for a trial of on-farm producer managed field nurseries.

The field nursery program served two principal purposes:

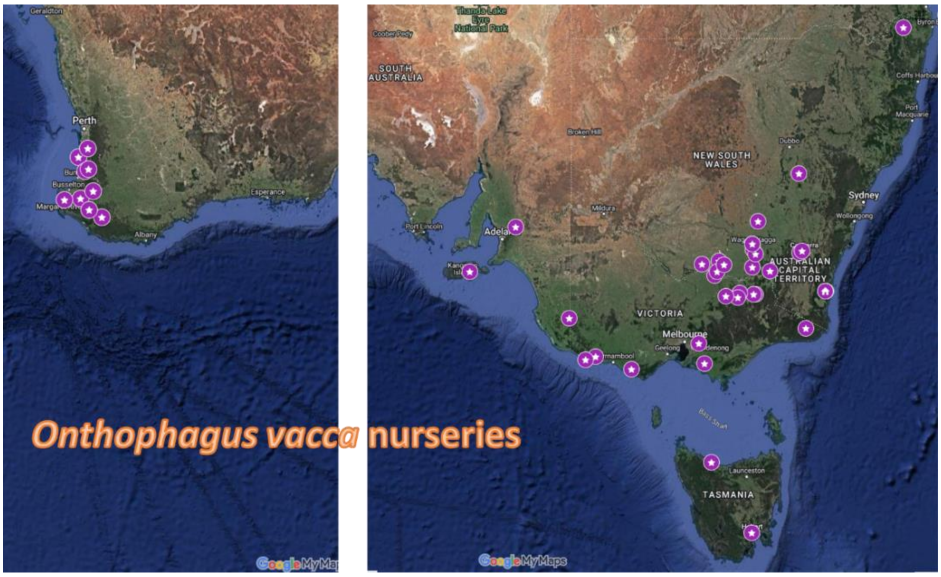
- to assess the performance of *O. vacca* initially in a wide range of environments in order to derive a direct evaluation (as opposed to CLIMEX predictions) of the limits to its distribution, to assess its breeding capacity and seasonal activity pattern in different climates and thereby identify the most suitable environments and timing for future releases.
- to ensure that the limited supply of beetles was used efficiently, paddock releases of 1000-plus beetles at numerous locations across southern Australia had been anticipated at the beginning of the program however due to low beetle numbers a nursery program with 50 beetles per nursery was developed so that a limited beetle supply could service southern Australia.

Nurseries were established in four southern states (WA, VIC, NSW, Tas) but not in SA since an established supplier (Creation Care) had an active distribution program there, leaving more beetles to be distributed between the four other states. Nurseries were established across a range of climates, from hot and dry (Geraldton, WA and Bonalbo, NSW) to cool and wet (Portland Vic and Burnie, Tas). An example of the portal above ground nurseries can be seen in Figure 1.

Figure 1: Field cages employed at numbers of locations in WA in 2019 and 2020 *(Photo Kathy Dawson, WCC).*

The on-farm producer nursery program delivered more direct data on the ideal locations for the exotic beetle species which contributes to providing the beetles with the best possible chance of successful establishment (example of distribution of *O. vacca* on-farm nurseries in Figure 2). However, establishment will not be able to be measured in the life of the project as this requires 8-10 generations/years.

Figure 2 *Onthophagus vacca* nursery sites across southern Australia



(Source Dr Russ Barrow, CSU)

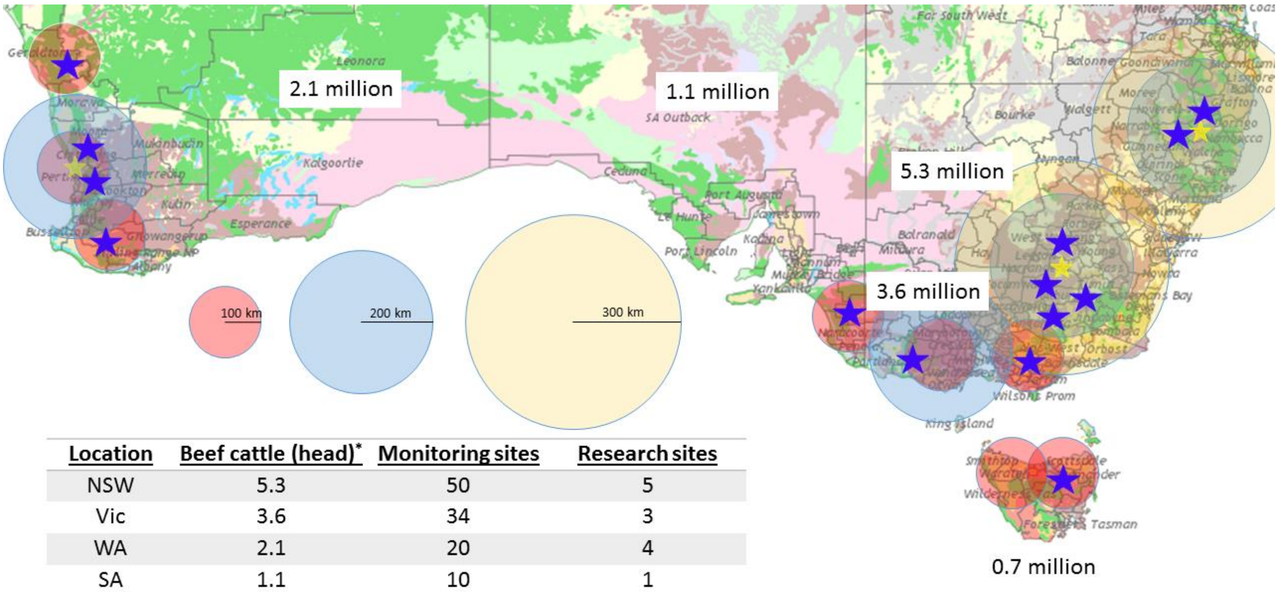
3.4 Theme 4 - Beetle Database: collection and collation

Theme 4 focused on the collation of data and information on dung beetle distribution, biology and ecology from a wide range of sources including reports, books and published articles, to provide a comprehensive dung beetle database. Newly collected survey data on dung beetle species, location, and abundance has been incorporated into regional mapping presented on the project website and information about Australian and imported beetles is accessible to users via a web-based interface.

Historic records of dung beetle distribution were collated and presented in geospatial maps on the DBEE website. Historical presence data was compiled from both published historic records of dung beetle distribution and observations from researchers and beetle experts associated with the DBEE project.

Field monitoring based on scientifically proven protocols were used to sample dung beetle species presence and abundance at least 120 sites. The monitoring collaborators employed the smartphone app developed specifically for the DBEE project, *MyDungBeetle* Reporter or *MyPestGuide* Reporter to record all trapping and monitoring activities. Monitoring sites were selected based on regional beef cattle and sheep numbers and soil type across southern Australia using national databases for guidance (see Figure 3). Livestock numbers were assessed at both the Natural Resource Management (NRM) Region level for coarse assessment and at a more detailed level through data mining afforded by Neil Clark-Kynetec Business Intelligence mapping tools. Consideration of soil types allowed assessment of impact of soil type on dung beetle activity and habitat preference by species. Site selection also considered rainfall and temperature gradients within soil type regions. The data from this field survey was then maintained in the Atlas of Living Australia (ALA) records.

Figure 3 Map showing the distribution of beef cattle and target areas for the monitoring sites and intensive research sites (indicated by blue stars), across southern Australia. The yellow stars indicate the location of the major partners involved in overseeing monitoring (UWA, CSU, UNE)



Location	Beef cattle (head)*	Monitoring sites	Research sites
NSW	5.3	50	5
Vic	3.6	34	3
WA	2.1	20	4
SA	1.1	10	1
Tas	0.7	7	1
NZ (NI)	(2.6)#	-	1

* MLA figures for Australia (https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/fast-facts--maps/cattle-numbers-map-2018-as-at-june-2017-data.pdf)

\# Stats NZ figures for New Zealand. North Island (NI) 2.6 million beef cattle (https://www.stats.govt.nz/information-releases/agricultural-production-statistics-june-2017-final)

Researchers then applied the dung beetle monitoring data to quantify the effects of climate and landscape as factors that may potentially have influenced species presence and abundance. Using all of this information researchers attempted to achieve the ultimate goal, to successfully predict species presence and abundance across the entirety of southern Australia, to aid on-farm management and identify gaps (spatial or temporal) in introduced dung beetle activity.

3.5 Theme 5 - Training, Education, Information delivery

Theme 5 focused on the development of educational information and generation of tools for provision of project outreach and training sessions to stakeholder groups supported by the dung beetle producer / stakeholder network across southern Australia. Project communication and outreach activities needed to be suitable for a diverse group of stakeholders including producers, researchers, students and citizen science. Educational training programs for youth, producers, outreach specialists and other stakeholders was further supported by development of identification guides, factsheets and a comprehensive project website. The www.dungbeetles.com.au website was developed as the principal repository for all information relating to dung beetles in Australia and has been designed and linked to relevant social media platforms including the project Facebook page and various Twitter handles, and provides content on dung beetle surveillance and monitoring, beetle identification and management, on-farm rearing as well as beetle procurement, and dung beetle distribution across Australia. In addition, workshops and outreach events were conducted at participating schools, and by associated Landcare, farming system and key producer groups in Australia and New Zealand.

Project communication and outreach activities were planned annually and material developed over the course of the project for the diverse group of stakeholders participating or interested in the project. Outreach activities were initially focused on utilising existing relationships with regional Landcare networks, farming system groups and livestock associations from northern NSW to Tasmania to southwest WA. Stakeholder interest in the project was generated by publication and distribution of a bimonthly project e-newsletter, which later became a series of MLA articles and newsletter updates distributed through the MLA communication channel. Media pitching aided the potential reach to a national (289M hits), and even international, audience with publications in newspapers, journals, magazines and regular radio and TV interviews.

During COVID19 imposed travel restrictions, outreach activities continued to deliver in educating producers and landholders on dung beetles but were undertaken via the internet through a series of webinars and on-line workshops. These workshops allowed for a much wider audience than the local targeted group as participants were able to attend from anywhere that the internet was available.

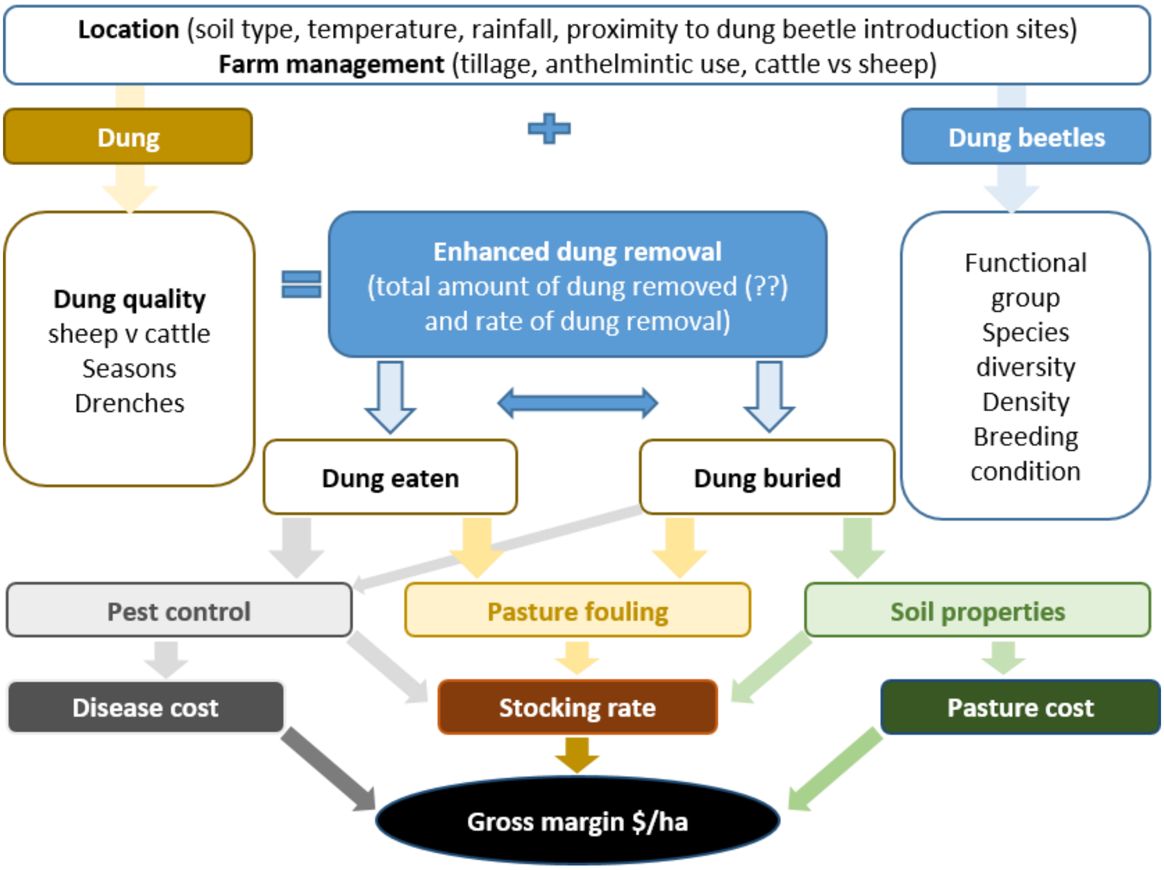
To respond to training needs of project stakeholders, educational tools including slide sets, worksheets, videos and posters were designed and improved over time for stakeholders. Tools to better identify beetles on farm, trap and monitor local dung beetle populations on-farm, and report beetle presence to the project database using the *MyDungBeetle* Reporter phone App were presented on the DBEE website for distribution and use by regional stakeholders. A pocket guide for beetle identification and regional dung beetle identification guides were developed on request from stakeholders to provide high quality imagery of specimens for ease of identification, A series of videos and work sheets to inform producers on beetle nursery design and establishment supported stakeholder interest in developing on-farm nurseries for beetle increase.

As the project evolved, a social media profile was established primarily via an active Facebook page and profile, managed by the outreach team.

3.6 Theme 6 - Quantifying Economic Value

Theme 6 focused on the assessment and quantification of dung beetle ecosystem services as on-farm economic services, and off-farm environmental and social benefits (see Figure 4). While the specific benefits of what dung beetles can potentially provide on farm are well understood, there has been little to no previous attempt to understand this value from an economic sense, and at a landscape and industry level. Understanding the value dung beetles provides has been critical for successful incorporation in farm management systems. This information will also be used to inform decisions about future research investments and adoption initiatives.

Figure 4 Components and inter-relationships of the various factors that influence the economic value of dung beetles



Understanding what research had previously been undertaken to quantify the economic benefits required a comprehensive review of existing literature, searching for scientific (taxonomic) names (Scarabaeidae, Scarabaeinae, Aphodiinae, Geotrupidae), and common name "dung beetles". The knowledge gaps identified in the review, provided the outline for the experiments required to allow measurement of the value of dung beetles environmentally, socially and economically at a producer level.

Laboratory experiments were used to assess the dung burial capacity of 15 introduced dung beetle species, under short term, controlled conditions. The goal was to quantify dung burial under various conditions. One application of the results of these experiments was to estimate dung burial across southern Australia, based on the predicted beetle abundance from the monitoring project.

Field experiments were used to estimate the dung burial of selected introduced dung beetle species (usually the most common) in southern Australia, under realistic field conditions over a 12-month period. The goal was to have data on the benefits of exotic dung beetles under conditions relevant to Australian livestock producers. These experiments were conducted at 10 field locations across a range of agricultural landscapes and climates – in regions surrounding Armidale NSW, Gundagai NSW, Culcairn NSW, Wagga Wagga NSW, Gippsland VIC, Inverleigh VIC, Struan SA, Perth WA, and Otorohanga New Zealand – which resulted in the applicability of research findings across most intensive grazing areas in southern Australia.

A lysimeter experiment was also conducted with four distinct soil types in soil columns maintained under field conditions over a period of 5 months in Wagga Wagga NSW. Utilising 48 soil columns, CSU researchers quantified the impact of a common introduced dung beetle (*Bubas bison*) in this region on water quality after permeation through four different soil types sown to winter annual pastures. Dung beetle treatments included dung plus dung beetles, dung alone and no dung beetles, and no dung and no beetles as a control.

Genetic analyses were used to measure the genetic diversity and population structure of four introduced dung beetles in Australia. These analyses were used to consider how beetles have established, and to determine adaptation to local conditions (of climate and soil types). A lack of genetic mixing defines a genetic 'population' and the distinct populations equates to a population structure. High levels of population structure, especially when corresponding to geography, indicates local adaptation. Locally adapted beetles are potentially less suitable for cropping and re-distribution to climatically different sites.

Economic analyses were used to estimate the value of beetles to livestock, dairy and wool farmers across southern Australia. A historical analysis was conducted to estimate the change in productivity of the land (stocking numbers) due to introduced dung beetles in one part of Australia (South-west WA), for the five years following release of the first dung beetle species (early 1970s). A subsequent current analysis was used to estimate the ongoing value of beetles across Australia, based on land area, economic inputs and income from livestock production (beef, milk, lamb, wool).

At the time the project was conceived ecosystems services were to be quantified in the laboratory, however, the value and relevance of laboratory experiments in quantifying these services was queried. This was highlighted by stakeholders present at the September 2018 DBEE project forum at CSU where a number of stakeholders questioned the relevance of proposed laboratory experiments. Feedback from the forum was addressed by project researchers by reducing the overall number of laboratory experiments and increasing the number and scope of proposed field experiments. Given this substantial change, the resulting dataset is among the largest—if not the largest—and most comprehensive experimental assessments of dung beetle mediated ecosystem services undertaken.

3.7 Theme 7 – Importation of New Species/strains

Theme 7 focused on the importation of new beetle species and strains to fill seasonal and geographic gaps in beetle distribution as we aim for sustained dung management throughout the year across southern Australia. Four new dung beetle strains/species were selected based on their efficiency at burying dung, seasonal activity and distribution in their native range.

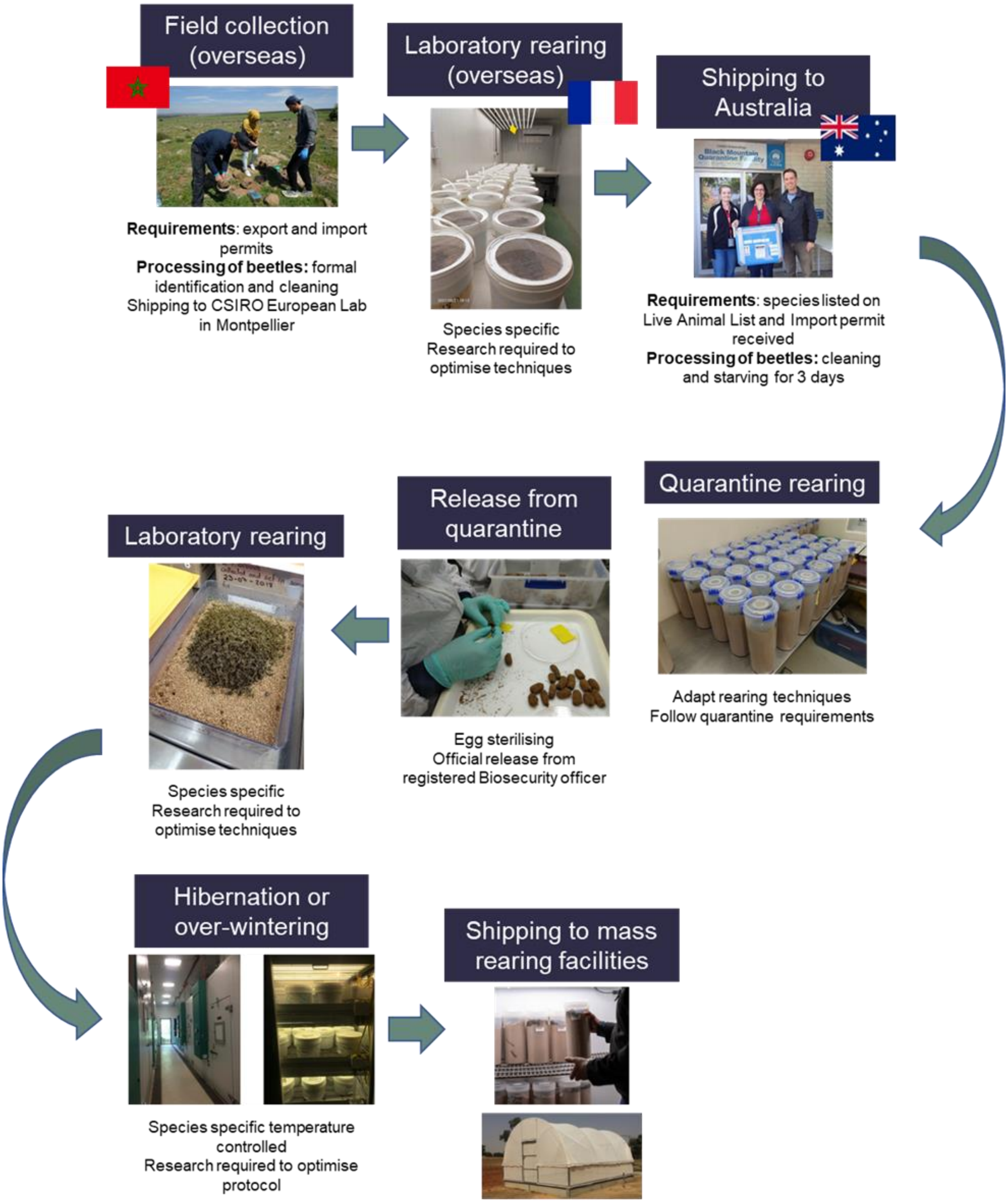
The selection of new species was undertaken using a combination of broad consultation (of dung beetle insect ecologists) and climate matching, to identify beetle species living in similar climatic conditions and soils. From this, dung beetle species were selected based on their specific biological and ecological characteristics (such as tunnelling or shredding dung) and the timing of emergence and activity range (i.e. the target has been for early emerging spring active species).

The process of importing live dung beetles into Australia is a complex process and is time consuming requiring several key steps and careful timing. Stringent prohibitions and quarantine restrictions apply, particularly for agricultural products that are considered to have the potential to introduce pests or disease. These are designed to protect our environment and agricultural industries from potential decimation or destruction. Collection permits and exportation permits from the source country and importation permits are required, depending on the countries involved. In this case, the dung beetles received into the Approved Arrangement site – the Black Mountain Containment Facility – did not leave quarantine and the eggs they produced were surface sterilized before they could be released for rearing. Utilising the latest quarantine procedures to complete this step is indeed time consuming but critical.

Once reared under laboratory conditions in Australia, dung beetles were multiplied at mass rearing facilities for eventual distribution to producers. Rearing dung beetles is a highly manual intensive and timely exercise as they require regular fresh dung throughout the active period and do not have the fecundity of many other insect species. The target is to produce a 10 fold increase in each generation.

Importation of the beetles was achieved through a collaboration between the CSIRO European Laboratory in Montpellier, France, CSIRO staff in Canberra, and the University Sidi Mohammed Ben Adbellah in Fez, Morocco and was initiated with considerable laboratory and field work. The background research required to import each species was considerable as each beetle species had unique dietary and life stage requirements. To maximise success, the activities of each partner were first well defined. The Moroccan team focused on field studies, the French team worked exclusively in the laboratory to develop optimal rearing protocols, while the Australian team focused on importation and ensuing activities (refer to Figure 5 Key steps of dung beetle importation process into Australia).

Figure 5 Key steps of dung beetle importation process into Australia



(Source: Dr Valerie Caron, CSIRO)

3.8 Theme 8 – Project Legacy

The extensive outreach activities will achieve an ongoing legacy of increased community and stakeholder awareness of dung beetle productivity and social benefits well after project completion. The tools and resources developed throughout the project will continue to be available to Landcare and other groups from the website, and are being utilised to promote the benefits of dung beetles across our landscape and work to fill the seasonal and geographic service gaps currently found across Australia.

Through these extension/outreach and distribution activities, a legacy network of industry stakeholders has been upskilled, motivated and resourced to continue to provide producers with access to locally adapted dung beetles.

The introduction of three new species timed to be active during peak pasture production in the southern systems will provide significant dung processing capacity in a period when current species are not active. In much of southern NSW, Victoria and South Australia, these three species will effectively close the last major seasonal gap in dung processing capacity. The establishment of the new species/strains will not be known in the lifetime of this project but the network of stakeholders to continue rearing and distributing will give the beetles the best opportunity to do so.

The development of cost-effective, reliable, safe and efficient importation process for new dung beetle species provides a pipeline for future importations, including building relationships with international collaborators with dung beetle research expertise and facilities.

In order to facilitate a quicker response for future importations of new dung beetle species, an additional 14 species have been submitted via application to be added to the Live Animal List. For the DBEE project this process took 12 months and is only the first step in seeking approval to import live beetles to the country.

The research activities have occurred at University of New England, CSIRO, Charles Sturt University, University of Western Australia and a large number of research sites or farms across southern Australia, yet the research findings will be applicable to intensive grazing regions across all of Australia.

4. Results

There are several clear key achievements that the project accomplished which has resulted in better outcomes for livestock producers. This was achieved in light of the extensive challenges around the COVID19 pandemic, difficulties around dung beetle rearing and numerous weather-related impacts (floods, tornados, hailstorm, drought, bushfires and subsequent destocking) across southern Australia. However, project partners adapted to these challenges by thinking innovatively and adapting activities to overcome these difficulties.

The three most significant impacts for producers resulting from the DBEE project are:

1. the increased producer awareness of dung beetles, their role and benefits, and ongoing capacity-building delivered through the training activities and communications and extension arm of the project.
2. The importation and release of new dung beetle species to fill the late winter-early spring activity gap in southern Australia
3. The calculation of the economic value of dung beetles at a landscape level.

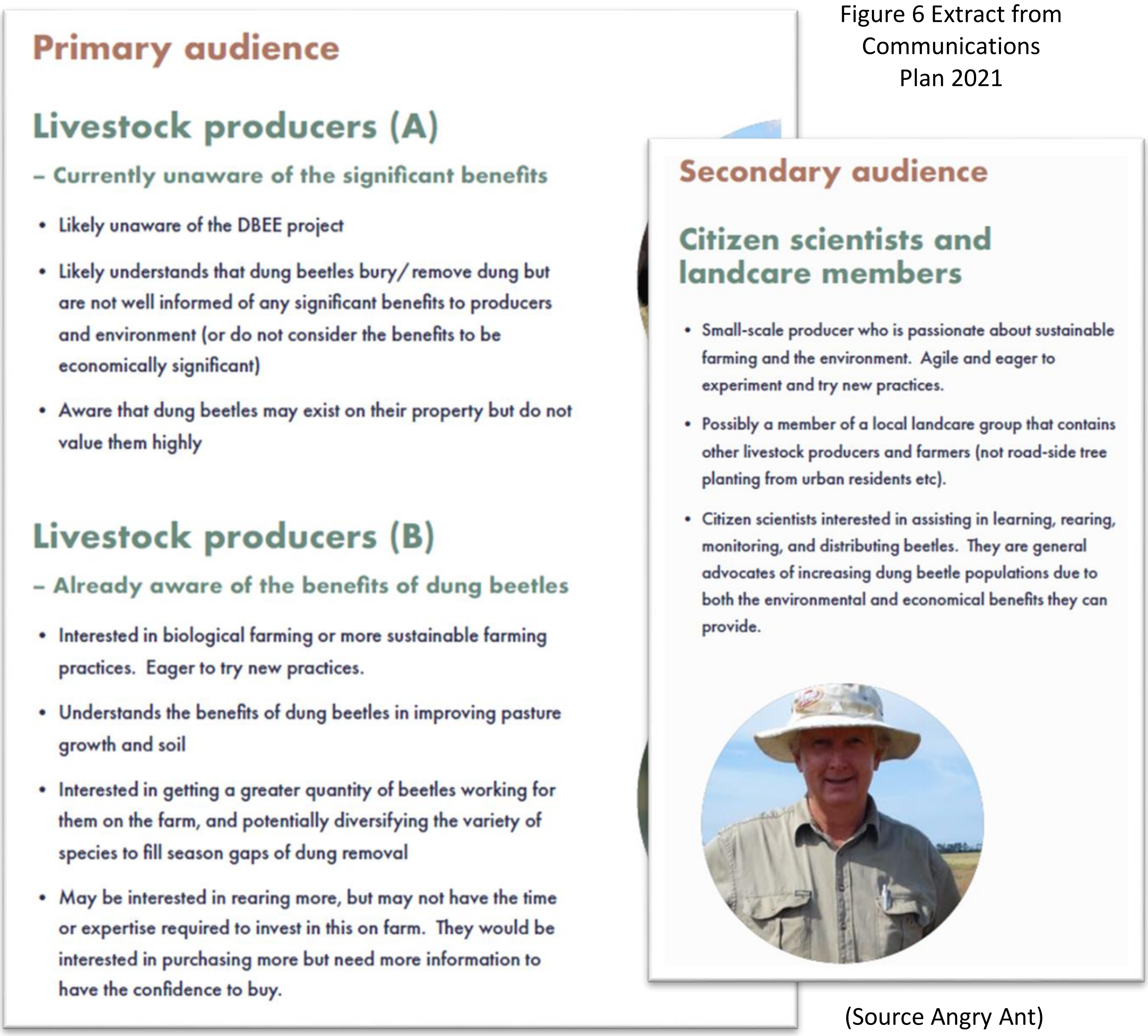
4.1 Producer Awareness - Communication and Extension:

Dung beetles are generally known by producers to provide a range of environmental and social benefits, but most surveyed had little understanding of detail or how to optimise these benefits. The underpinning value of dung beetles in our grazing system is well understood, and backed with over fifty years of research, but often hasn't translated to individual producers appreciating the range of services they can or are already providing. To instigate a practice change, producers need to be aware of the benefits of dung beetles and the value they offer, and have the knowledge, motivation and tools to undertaken change. The project highlighted that many benefits provided by dung beetles are taken for granted and not missed until the system is disrupted (such as the 2021-22 floods of northern NSW and Southern NSW/Victoria). In both cases a total loss of dung beetle populations and the resulting increase in pasture fouling and pest fly numbers raised questions as to what had gone wrong.

Led by Theme 5, the project group worked with communication, marketing and web designer specialists to produce targeted content and implement and deliver this to livestock producers. While it was obvious that the project's primary audience was livestock producers (specifically beef cattle, dairy cattle, and sheep, but other industries are also impacted such as goats, horses, alpacas, etc), these were further broken down into those that were already aware of the benefits of dung beetles and those who were unaware (Figure 6). Early engagement with producers indicated that there were far more in the latter category than the first, so initial activities and messaging focused on raising the awareness of dung beetles.

Increased awareness of dung beetles and their benefits through direct contact with >2500 producers and 700+ high impact media outputs.

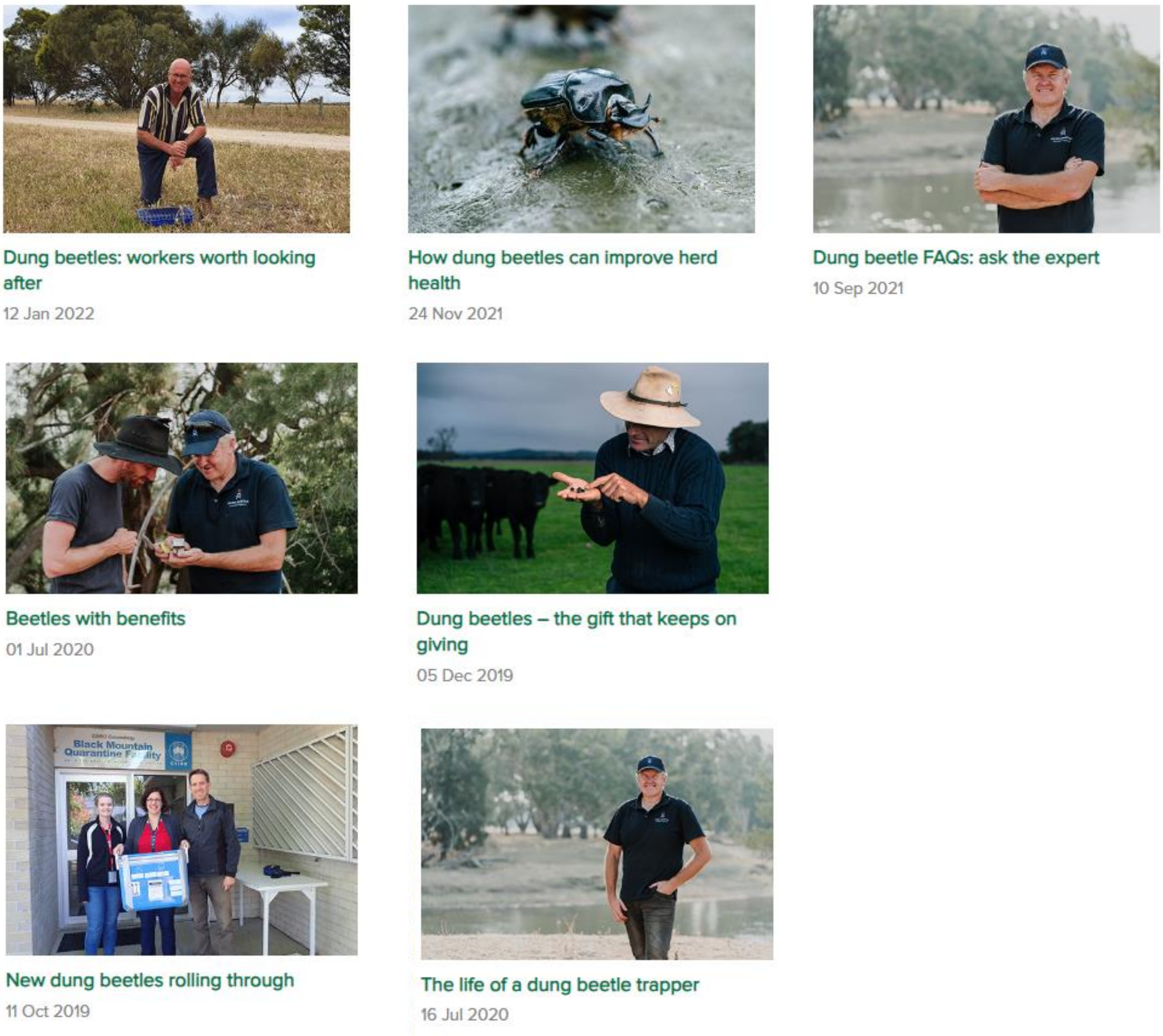
Figure 6 Extract from Communications Plan 2021



(Source Angry Ant)

The DBEE project facilitated distribution of a quarterly e-newsletter and regular news updates, supported by media articles for distribution through the Australian rural media network (refer to Appendix 8.1 Project media, communication and extension). One story that was well received by the media and industry was the arrival of the second beetle species to quarantine in Canberra. Media hits at this time reached over 1M Australians in 24 hours due to TV, radio, newspaper, magazine and on-line media. Remarkably, the total outreach audience for the six months up to April 2022 was estimated at over 77 M, in contrast to previous media in the first six months reaching approximately 1-2M. Audience increase was associated with media through ABC publications and radio interviews, Associated Press as well as MLA based newsletters and magazine articles developed specifically for target MLA stakeholder audience by DBEE project communication team experts (refer to Figure 7 example of articles published via MLA newsletters).

Figure 7 example of articles published via MLA newsletters



As awareness increased novel educational tools were developed in the form of pocket identification guides (3000 distributed for free), electronic identification resources, videos, worksheets, newsletters, news and information on dung beetle distribution and purchasing, and a project photo gallery. These tools were focused on educating land managers and guiding management decisions on farm, however, were generic in nature. Regionally specific guides were developed as survey data highlighted there were a small number of species that were likely to be established in any one region. These guides allowed producers and outreach groups to focus their attention on species that were most like to be found in their region and not all the exotic species introduced to Australia.

The DBEE project website www.dungbeetles.com.au was the repository for these digitally-based educational tools. The website has supported stakeholders (>29,000 users accessed the site since 2019) by providing easy access to over 30 digital resources available to project stakeholders including:

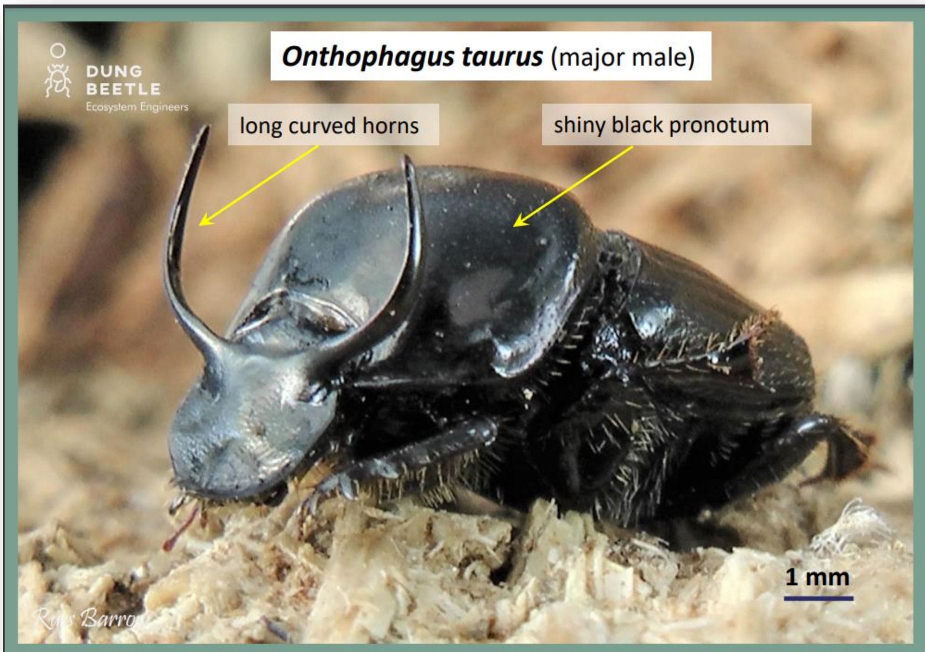
- Regionally specific exotic dung beetle identification guides (Figure 8) (NSW / Central West, North West, Northern Tablelands, The Riverina, SA / South East, TAS / Tasmania, VIC / East Gippsland, South West, WA / Northern Agricultural Region, South West)
- Historical mapping of dung beetle distribution by species across Australia and current project monitoring results across southern Australia

- Various protocols for beetle trapping to establish which dung beetles are present at any field site (including those for replicated experimentation and those simplified for stakeholders)
- Beetle identification guide to provide detailed graphics for assistance in identifying common exotic (and a 10 native) beetle species (25 species) (example in Figure 9)
- A video gallery covering topics including:
    - Project introduction and ecosystem services provided by dung beetles,
    - technical videos on:
        - Trapping and release of dung beetles on-farm,
        - FAQs :
            - What is a dung beetle?
            - Why import dung beetles?
            - How do dung beetles prevent fly infestation in paddocks?
            - Where do dung beetles go between seasons?
            - Do you need more dung beetles on your property?
            - How long does it take for beetles to be effective?
        - Timelapse videos of beetles processing a dung pat, and
        - Recorded information sessions from researchers, at workshops held mid-way through the project:
            - Importation of dung beetle species
            - Featured extension activities through formal project partners
            - Ecosystem service evaluation
            - Delivering beetles and services to producers
            - Beetle monitoring and surveillance
- A compendium of technical reports associated with dung beetle research performed in Australia
- A database of published journal articles (containing over 1700 global research articles) Note: access to actual journal articles limited by copyright.

In 2020, a project Facebook profile was managed by the regional outreach team. The Facebook page has achieved reasonable success with over 1300 users and over 8700 access hits in total.

Figure 8 sample of a regional guide

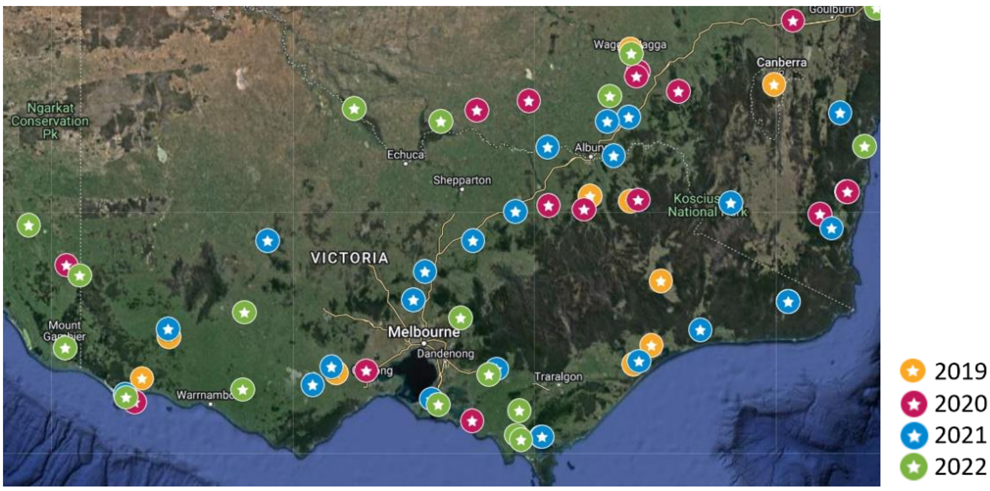
Figure 9 Example of identification guide image (Onthophagus taurus) (Source Dr Russ Barrow, CSU)



The DBEE project has developed a national and regional network of Landcare, Farming System and producer groups forging regional ties across southern Australia. An estimated 60+ regional groups participated in field days, workshops, webinars and dung beetle monitoring programs (see Figure 10). On the ground outreach staff held field days, on-farm training and workshops in association with producer-based groups, resulting in over 100 face-to-face outreach events and numerous follow-up training sessions to establish numerous on-farm nurseries across southern Australia. (see Figure 11). These supporting groups have also built up their knowledge and expertise of dung beetles to continue the education of producers in their regions along with industry experts from existing organisations (such as Dung Beetle Solutions International, Creation Care, SoilCam) and new organisations (such as EcoInsects).

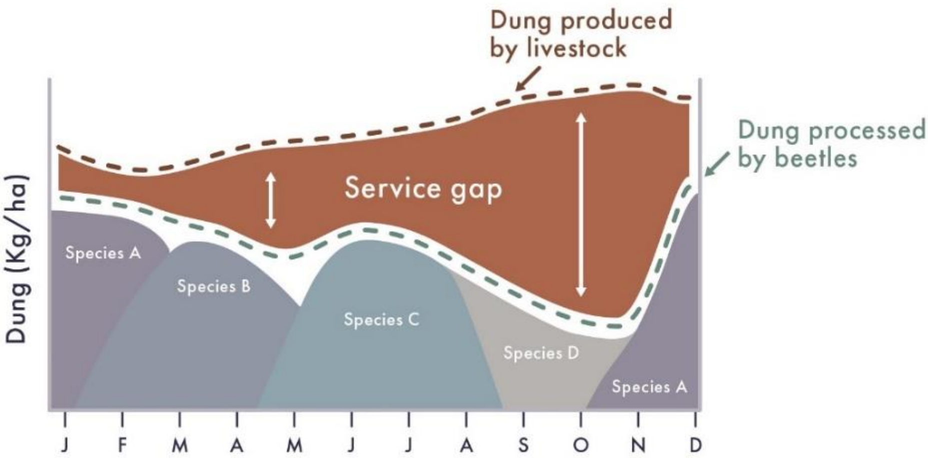
Figure 10 Extension network developed with Landcare, farming system and producer groups, schools, and other stakeholder groups

Figure 11 Location of outreach activities in eastern states. Each colour represents the year extension activities occurred. (Source Dr Russ Barrow, CSU)



Outreach activities were performed by distance education as well as in face-to-face events across southern Australia, with greatest activity in NSW, and VIC, but activities were also held in SA, WA and TAS. Travel restrictions as a consequence of COVID19 resulted in a series of webinars and on-line workshops held from 2020-2021 (+10 training events). Face-to-face events were the preferred method of contact with stakeholders and were extremely popular with over 100 on-farm demonstrations, workshops, training events and field days with outreach to over 2500 total participants and follow-up to these events through worksheets and published newsletters. Key training topics of interest include beetle identification, beetle management on-farm, demonstration and establishment of on-farm nurseries for beetles, and beetle re-distribution. Many producers did not know that every species is active in a specific time period/season and any time when dung is left on the surface unprocessed is a service gap that needs to be filled (see Figure 12).

Figure 12 relationship between available dung and dung beetle species



(Source: EcoInsects)

In summary, extension activities included 731 media appearances (television, radio, newspaper), 143 stakeholder presentations and webinars, 42 field days and workshops for producer groups, 41 brochures and newsletters, an active social media presence and development of a website. Additionally, project members delivered 12 presentations at scientific conferences and published at least 8 peer-reviewed papers, with further manuscripts in preparation.

At the end of the project, interest in project outreach remains keen, and on-the-ground outreach staff are continuing to provide on-farm outreach with additional project support provided by the DAWE Smart Farms Community Grants Program, with support received in Central NSW and southern QLD projects. It is hoped that the legacy of this project will result in continuing emphasis on stakeholder outreach and extension, and development of additional regional and national educational tools.

One of the key messages that the workshops and online forums has introduced to landholders, is that "dung beetles" are not one species actively processing dung all year, but a successful population is multi-species covering different times of the year.

4.2 Distribution of beetles:

The improved distribution of dung beetles across all seasons and a wide area of livestock regions in southern Australia was a key outcome for the project. Apart from introducing the new species suitable for spring activity, identifying gaps with current species temporally and spatially required a network of partners. The project formed collaborations between land management organisations, commercial dung beetle providers and researchers to share knowledge and build capacity for dung beetle distribution. Existing dung beetles (*Onthophagus vacca* (French strain)*, Bubas bison, Bubas bubalus, Copris hispanus* and *Onitis caffer*), were either reared or field collected and redistributed to fields and farm nurseries on over 100 geographically distinct sites across NSW, ACT, Vic, SA, Tas and WA. Identification of suitable sites was based off previous surveys and climate mapping; however, the climate mapping data had not been updated for a number of decades. As climatic conditions have been changing, it is possible also that the range for these species has also changed. Investigating the limits of these species indicated locations where the species should establish but for whatever reason they haven't migrated or been introduced or successfully established previously.

4.2.1 Bubas bison

For example, project surveys have shown *B. bison* was well established in a broad area around Wagga Wagga but was absent in regions east of the Great Dividing Range. Field cropping and release of *B. bison* into regions where they have not been previously observed occurred on scale with an estimated 50,000 released at 67 sites (see and **Error! Reference source not found.**). This project has already met some initial success with beetles recovered in a following mid-winter survey, approximately 12 months after their initial release.

With the assistance of the Cowra Men's shed, a series of on farm field cages for mass rearing *B. bison* were established in the Cowra region. In addition, field cages were established in association with two local high school biology departments. The incidence of larval diapause (i.e. a 2-year life cycle) is being monitored in field cores inoculated at the same time as field cages were established.

Other distribution of *B. bison* colonies occurred to multiple sites in Victoria, southern NSW and central NSW,

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Figure 13 *Bubas bison* redistribution and nursery sites through NSW & Victoria

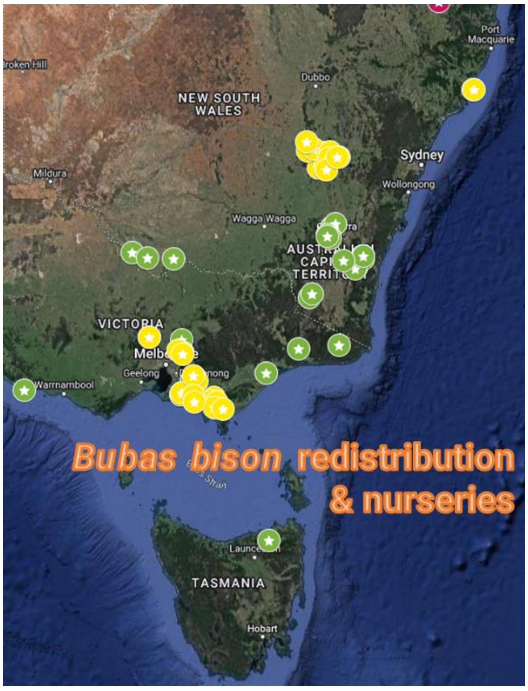


Figure 14 Bubus bison caught in a sand trap for redistribution

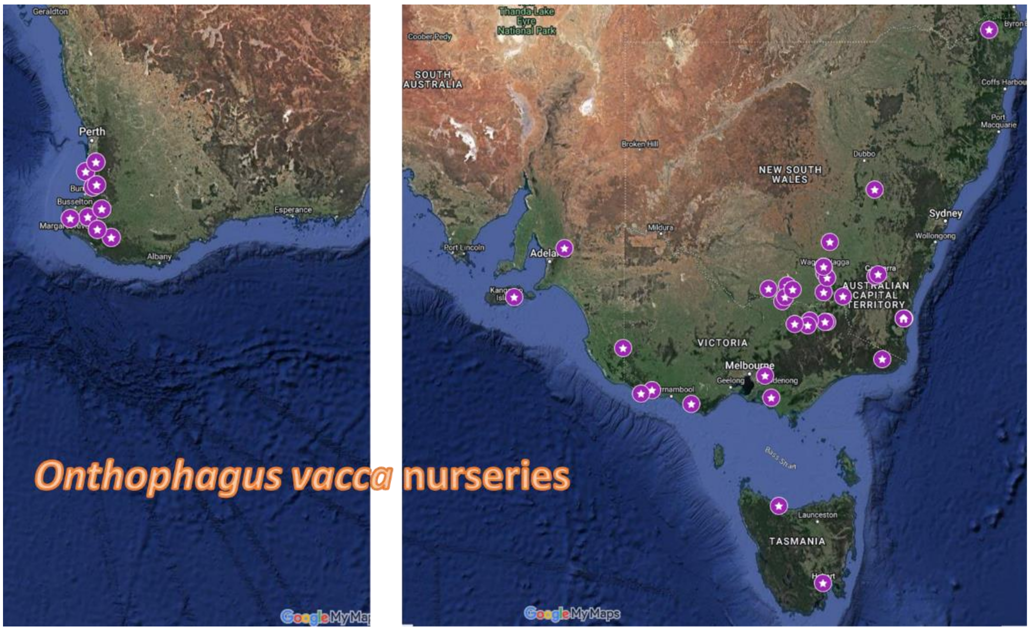
(Source Dr Russ Barrow, CSU)

4.2.2 *Onthophagus vacca* (French strain)

This species had been imported during the previous MLA funded project (2013-2015) but a combination of limited funding and a lack of knowledge (at the time) on rearing meant that *O. vacca* had not been bred and released to even a proportion of its full potential as a spring active beetle for southern Australia. Working with the small numbers of *O. vacca* already in Australia (thanks to private dung beetle breeder Greg Dalton from Creation Care), DBEE identified a large number of potential sites for release. Rather than releasing dung beetles in 500+ colonies to field sites, the project instigated an on-farm protected field nursery setup with producers. This approach de-risked the expansion of the species by working to identify the regional limits for successful breeding and establishment. The on-farm producer nursery program had mixed results for the project. The *O. vacca* farmer nursery program ran for 2 years but many of the participants had dropped out by the end of year 1 and a number of nurseries were poorly managed and produced no beetles. Despite the mixed results, the nurseries provided a highly informative account of the field biology of *O. vacca*. Nurseries were established across a range of climates, from hot and dry (Geraldton, WA and Bonalbo, NSW) to cool and wet (Portland Vic and Burnie, Tas) in an attempt to test the boundaries of the climate mapping for the species (see Figure 15).

The conclusions from this 2-year experimental field program were that the optimal field conditions for the establishment of *O. vacca* are cool moist environments where *Onthophagus taurus* is relatively scarce. Post-diapause *O. vacca* adults will emerge in August-September when they will proceed to feed and breed. Egg-to-adult development will take 2–3 months producing progeny that can be expected to emerge in December through January. Newly emerged adults will continue feeding to March/April before spending the next 4–5 months underground, during which time diapause is completed. It is unlikely that the species will persist in hot, dry environments. A draft protocol and progress results are presented in Appendix 8.4 Farmer Nurseries Protocol: On-farm producer-managed field nurseries for Onthophagus vacca and other species and 8.5 Results of on farm producer nursery experiment.

Figure 15 *Onthophagus vacca* nurseries sites across southern Australia



(Source Dr Russ Barrow, CSU)

4.2.3 *Copris hispanus*

Copris hispanus is one of the largest dung beetle species introduced to Australia and up until this project, has been restricted to a small area near the town of Williams in Western Australia. The difficulty in rearing and re-distributing this species is demonstrated by the limited success in rearing and failure of redistribution during the WA-Dung Beetle Project (1990-1994), and field release at six sites in WA by DPIRD (2014).

There were five field release sites of *C. hispanus,* along with attempts to mass rear them in the laboratory. Lab rearing proved a slow and laborious process and the *C. hispanus* was relocated to the field at Manjimup, WA and to field cages at Portland, SA. The performance of the beetles in these environments continues to be monitored. Evidence of continued dung burial activity has been observed at Portland. Moderate field populations (if the beetles establish) are not likely expected for at least a decade, due to the slow rate of reproduction in the field.

4.2.4 *Onitis caffer*

There were 15 field release sites of the summer-rainfall strain of *O. caffer* but no field releases of the winter strain (see **Error! Reference source not found.**). Field surveys have revealed that *O. caffer* is much more widespread than previously believed. Though the beetle is not easily trapped, field walks reveal their presence. Field populations have been cropped at Kingaroy, Qld and collaborators have established NSW field nurseries at Port Macquarie (two) and at Bonalbo. The Old Bonalbo breeding has been successful and approximately ten new on farm caged colonies have been established by the Landcare group Border Ranges Richmond Valley Landcare Network (BRRVLN) Inc. However, the exceptional and extensive flooding in 2022 has put many of these colonies at serious risk of failure. A southern strain of *O.* caffer from Araluen, NSW was used to establish a nursery in West Gippsland, Victoria. The *O. caffer* nurseries in NSW are expected to provide sufficient beetles for a field release.

4.2.5 Geotrupes spiniger

G. spiniger is one of the four deep tunnelling dung beetles found in southern Australia. The beetle is capable of shredding and burying large amount of dung offering multiple ecosystem benefits. The native range of this beetle is broad, from Europe through the Middle East but in Australia it is established only in a small number of regions. Mapping shows a much wider climatic area that the species could theoretically spread to and occupy, offering the opportunity for expansion of the beetle's range. *G. spiniger* colonies were distributed to nurseries in Central Tablelands and Riverina, NSW (Figure 16).

Figure 16 *Geotrupes spiniger* nurseries set up in NSW

(Source Dr Russ Barrow, CSU)

In total more than 240 release sites have been serviced with these various dung beetle species within the DBEE program, exceeding the contracted number (which was 100) but establishment will take many generations and years to confirm.

4.2.6 New imported species

With the new beetle species still coming through Quarantine and mass rearing in 2022, the project released an Expression of Interest (EoI) for land management groups or individuals to take on the rearing and distribution of these beetles. The project received 42 EoI's from a wide range of groups and locations which was beyond expectations. A project working group considered the EoIs in relation to their track record of successful rearing and the suitability of the climate in their location. Two were assigned as 'Tier 1' (Cannibal Creek Landcare and EcoInsects) to be handed beetles in the summer of 2022/2023 and a handful as others selected to receive beetles in Spring 2023. In January 2023, a consignment of 390 *O. vacca* from the CSIRO facility were handed over to Cannibal Creek Landcare (west Gippsland, Victoria). An illustrated fact sheet was prepared for use by legacy partners (Appendix 8.3). This constitutes a distillation of the practical experience of the project team from rearing and field release efforts, and the wider technical review process that led to the review paper.

It is planned to send available stock of *O. m. subsp. andalusicus*, as well as *G. sturmi*, to additional legacy partners in Spring 2023.

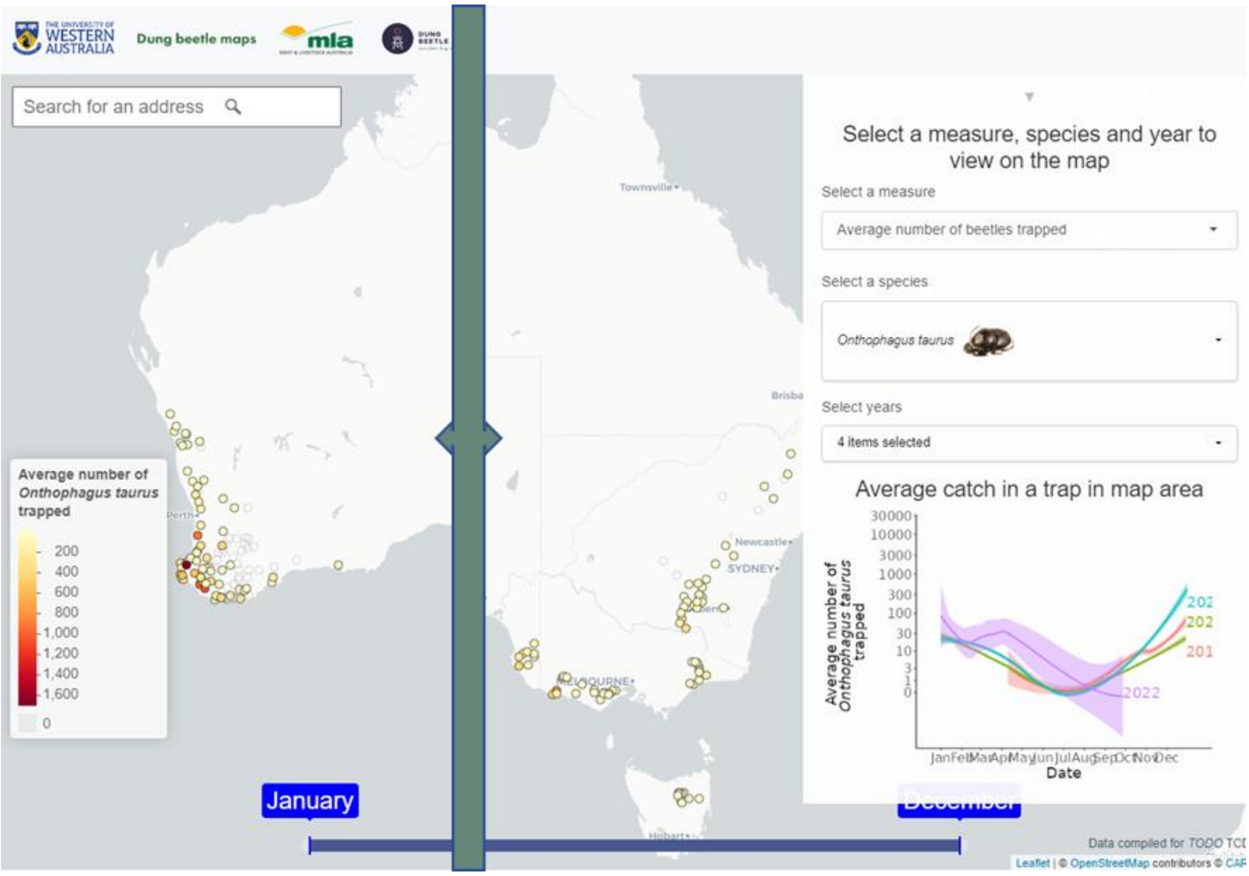
4.3 Monitoring program and mapping:

The DBEE program offered a unique opportunity to provide a detailed and widespread snapshot in time of the dung beetle populations (species, spread and abundance) across southern Australia. Since the first introductions of dung beetles in Australia in the 1960's no surveys of this type of scale have been attempted. Through a combination of traditional in-field trapping and physical identification combined with modern techniques of mapping, modelling and genetic analysis, this survey had the potential to provide a comprehensive understanding of:

- What species of introduced beetles had established where and in what sort of abundance.
- The timing, seasonality of each species in each area and potential adaption to environment.
- The service and dung processing gaps that exist across the landscape and farming regions.
- The monitoring data was also utilised in calculating the economic value of dung beetles.

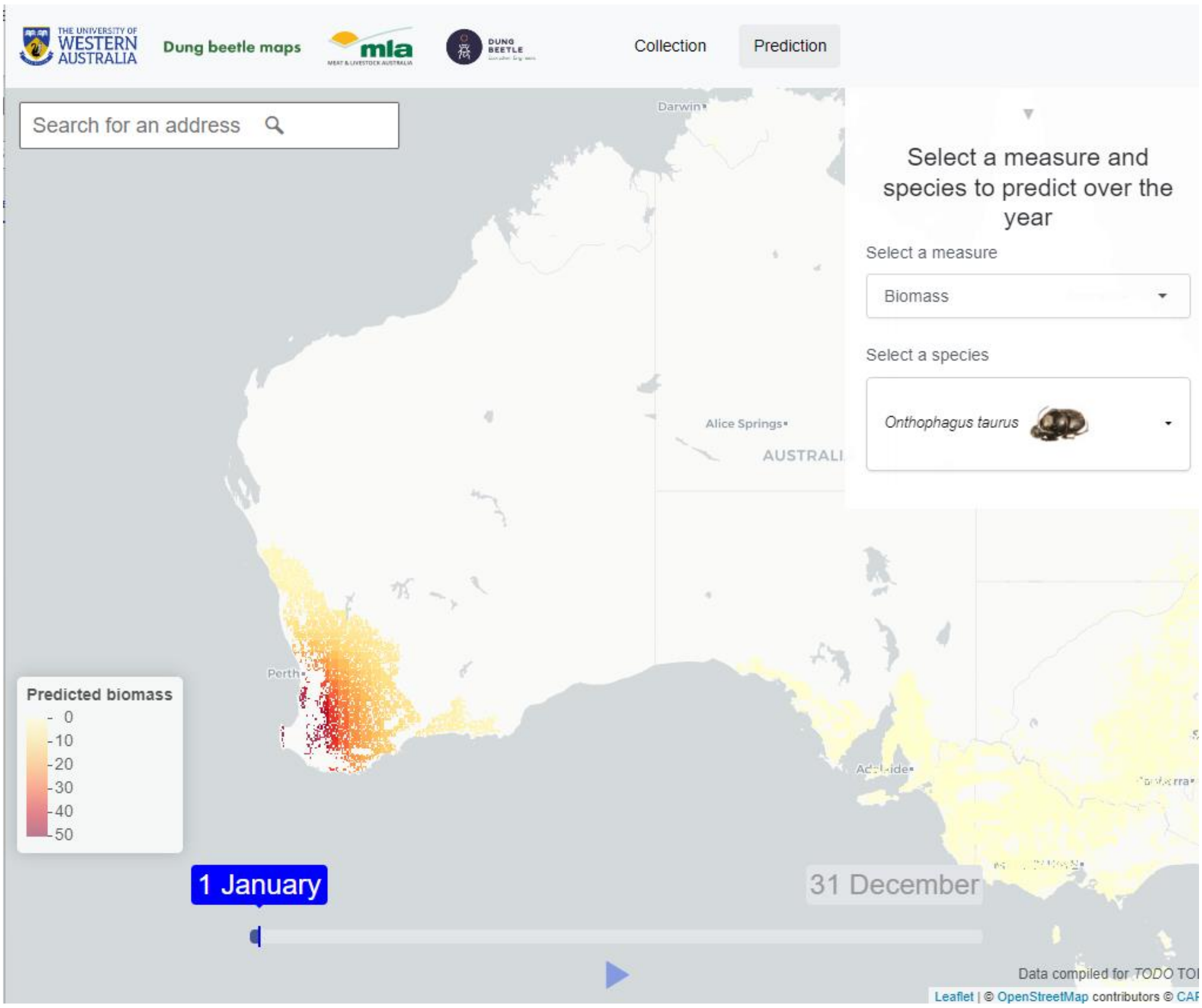
Utilising monitoring traps set for 24hrs, project partners, farming system groups or private landholders set traps at 420 sites. Sites were allocated according to livestock numbers, which would represent the largest source of dung to be processed and thus, the areas of greatest need of dung beetles. Not only were static sites selected to cover as much of the grazing landscape as possible, but transect surveys were also used. These surveys along hundreds of kilometres of highways /roadways supported the static traps to identify changes in beetle populations due to changes in topography, soil type, etc. Entomology trained researchers processed 6,613 samples identifying and counting 1,059,772 exotic dung beetles, from 190 monitoring sites. A further 817 site samples (includes transect samples) were identified by project partners on a less frequent basis. This is a significant achievement, providing one of the largest databases of dung beetle presence and abundance for a single country. Such a large data set is difficult to analyse and extrapolate practical outcomes. Therefore, researchers developed and deployed an online dashboard (known as Dashboard 2.0) to communicate the monitoring project data (Figure 17) (https://dungbeetles.shinyapps.io/dungbeetlemaps/). This would enable a specific producer in consultation with the extension team to understand which species they will be missing and likelihood of establishing them on their own farm and the benefits of doing so (filling gaps in dung processing).

Figure 17 Example of survey data available on Dashboard 2.0 for *O. taurus* showing incidence and population caught in traps over multiple years. This tool highlights the impact drought years in the eastern states in particular had on populations.



The dashboard displays the data from the monitoring sites, has options to consider numbers and biomass of beetles, and allows data from different years to be displayed for comparison. Most importantly, the dashboard shows estimates of beetles across southern Australia (numbers and biomass of beetles are modelled from the monitoring data), which allows any farmer to consider dung beetle activity on their own farms over the year (Figure 18).

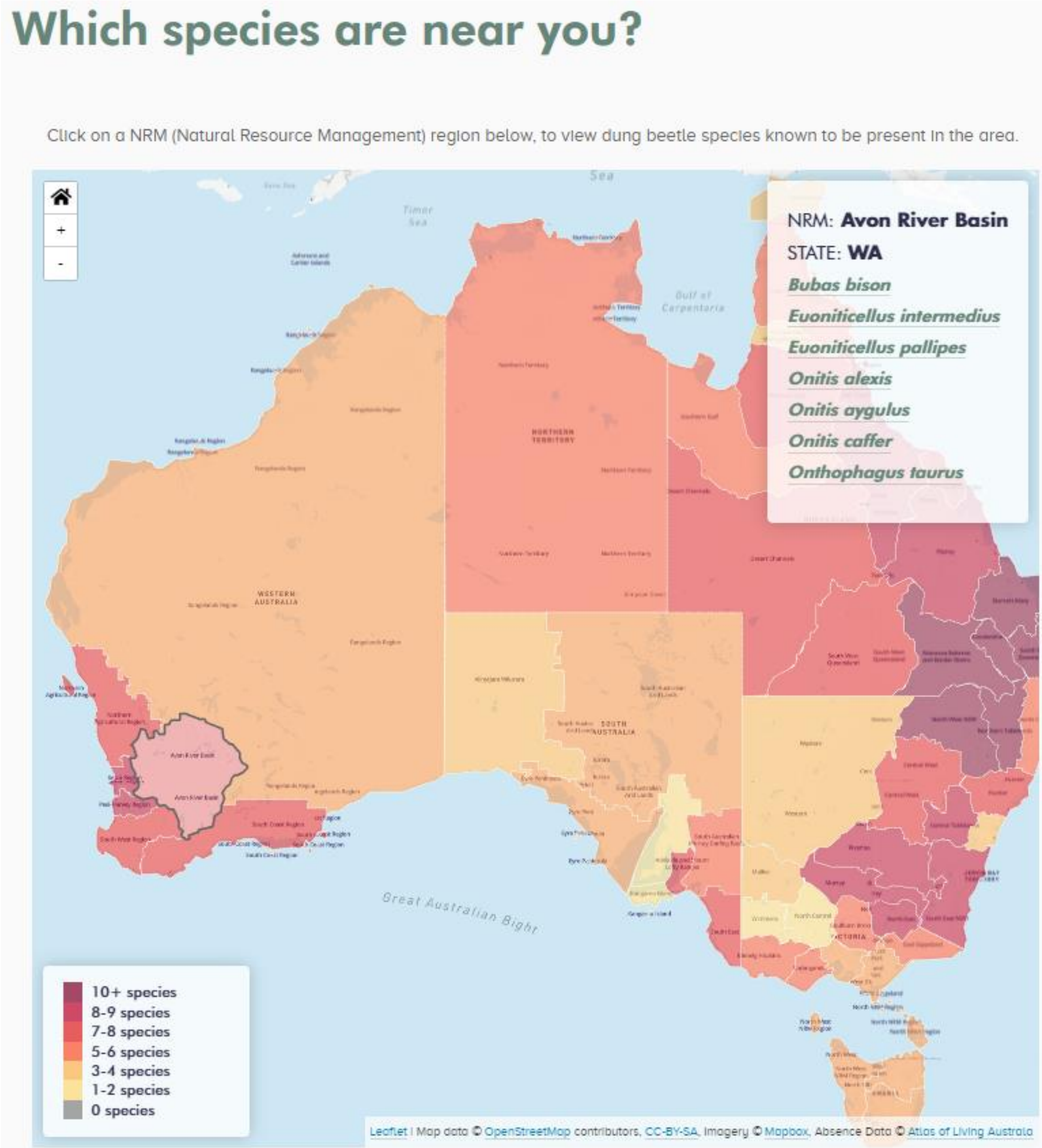
Figure 18 Predicted location of O. taurus as presented on Dashboard 2.0. The data is represented temporally using a video function seen on the bottom of the image.



Data from the monitoring has also been collated and uploaded to the Atlas of Living Australia website, which will serve as the repository of monitoring data post the project. The collected specimens that have been processed are being preserved for future research activities, providing a unique point in time dung beetle reference for the Australian landscape. By understanding the spatial and temporal distribution of dung beetles, the project has worked with landholders and community groups to establish rearing facilities to continue to fill identified gaps in beetle activity.

Prior to the generation of Dashboard 2.0, and still available on the DBEE website, are NRM based maps showing historical exotic dung beetle distribution. Collating records of dung beetle sightings from ALA and other reliable sources (for example the Queensland Dung Beetle Project 2001-2002) with the observations from the DBEE project, the geospatial maps have been created on the DBEE website. The map shows where introduced dung beetles have been found in Australia at the level of NRM units. It should be noted that the absence of a dung beetle species in a particular NRM may reflect a lack of records rather than a true absence of a species, and that a specific species may not be present across an entire NRM (Figure 19). This mapping provides a landscape level overview that can be distilled down with local surveys by producers to identify possible species to fill any gaps.

Figure 19 screen shot from www.dungbeetles.com.au showing historical beetle distributions



Most of the sites utilised for the survey program were private farms, with the monthly collection of samples done by a network of farming systems and Landcare group partners. The engagement of these groups, usually done in conjunction with a workshop presentation and field walk, meant that the survey activity itself became one of the most critical producer engagement tools of the DBEE program. Producers became engaged in this process and often continued to monitor across their property and had them questioning their livestock management particularly in terms of drench management.

4.4 Ecosystem service evaluation and quantify economic environmental and social benefits provided by dung beetles

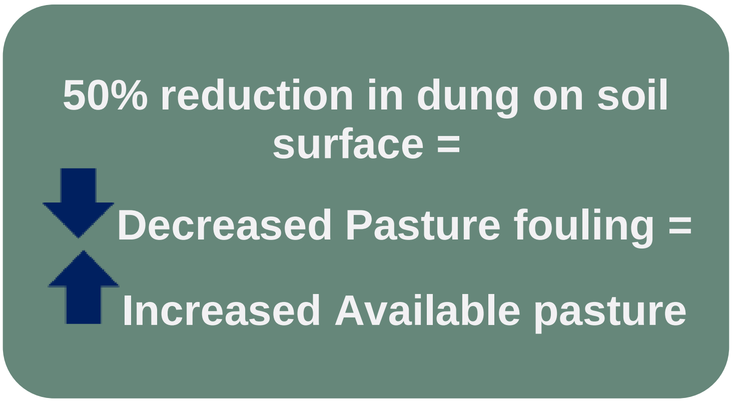
To quantify the economic, environmental and social benefits provided by dung beetles, researchers started with a review of existing literature. The review found over 4500 papers using the scientific (taxonomic) names, but about half that number when using the common name 'dung beetles'. A key finding of this review was the limited number of studies (39 total, with 29 in peer-reviewed papers and 10 in the grey literature) that quantified the benefits of dung beetles in Australia under field conditions. Reported benefits ranged enormously across studies. Dung removal (usually dung burial) is the most important and commonly measured variable, and this varied from 5 to 98% of the dung. Soil nutrients were the next most commonly measured variable. Soil nitrogen was reported to increase between 0-100%, phosphorus increased 450% (one study) and carbon increased 0-35%, while potassium levels were reported to decrease 10% (one study). Plant growth increased between 16 to 280%, while bushfly larval mortality was 30-97%, and nematode larval mortality was 37-93%.

The wide variation in results was likely due to the range of experimental conditions, especially quantity of dung supplied, various beetle species, and duration of experiments. Almost all studies were at three sites in Australia. The report showed a paucity of quality information on dung beetle benefits in Australia and meant there was very little existing data to work with.

The lack of existing data required a large number of field and laboratory experiments to be conducted addressing the multifactorial ecosystem services provided by exotic dung beetles. The field experiments completed, conducted from locations from Perth to Auckland, represent the largest study into the benefits of dung beetles regarding soil nutrients and pasture growth. Unlike most other large-scale experiments of this type, the experiments conducted by the DBEE project involved intensive sampling of multiple services over an extremely large area for a year (see Figure 20)

Figure 20 Field research site setup in New England Tableland area in northern NSW (Photo Zac Hemmings, UNE)

The results from the DBEE field experiments indicate that a key benefit of dung beetles to Australian and New Zealand pastures is the approximate 50% reduction in dung on the soil surface, which reduces pasture fouling. In addition to the increase in pasture availability, significant improvements in pasture growth were noted at two of three locations in the Riverina (NSW) but not across all experiment sites.



It is generally understood that dung beetles increase plant growth, however, the influence of dung beetles on plant growth can be extremely variable. There are many factors that influence the dung beetle-plant growth relationship, such as soil type, dung type and water quantity. This suggests that the general understanding of the dung beetle-plant growth relationship may be more nuanced and conditional than realised. Using a systematic review and meta-analysis to determine the effect that dung beetles have on plant growth, it was found they increased plant growth by 13.5%. In addition, the results suggest dung beetles may increase soil phosphorus. In field experiments conducted in NSW, improvements in soil phosphorous were noted at different monthly intervals in two locations in the Riverina. This work is now in preparation for submittal to the journal *Agriculture*. These mixed results highlight the variable effects of dung beetles on ecosystem services.

In valuing the total economic benefits of dung beetles, the approach was to estimate a flexible total revenue function that included all farm input variables, all prices, quadratic terms of inputs and prices, and all interactions. The full model proved to be infeasible due to the large number of variables, and models with improved grazing and breeding livestock numbers were found to account for approximately 80% of the variation in total revenue. Therefore, simpler versions of the model were used. The final estimates of the economic value of dung beetles are based on an interaction between estimated mean daily dung beetle biomass (from monitoring data) and the area of improved grazing. This total revenue model produced plausible estimates of the value of dung beetles for all states apart from South Australia (Table 1).

Table 1 Annual total revenue value of dung beetles ($ millions) for each state in three Agricultural Census years. The values in parentheses are the number of SA2s included in the analysis.

State	***2010-11***	***2015-16***	***2020-21***
NSW	160 (300)	89 (248)	140 (245)
Victoria	405 (244)	189 (201)	323 (201)
South Australia	NA	NA	NA
Western Australia	89 (92)	104 (72)	134 (134)
Tasmania	86 (66)	57 (62)	83 (58)

Source: ABS Agricultural Census data in three years: FY2010-11, FY2015-16 and FY 2020-21 with additional values included from the ABARES AGSURF database.

The economic value of dung beetles in southwest WA was conducted as part of a PhD thesis and found dung beetles were correlated with increased stocking rates. This analysis compared stocking rates aggregated across cattle and sheep between treated (dung beetles present) and non-treated (dung beetles absent) shires in the agricultural census data. The approach for present value across southern Australia found that dung beetles increased revenues from all livestock products (beef, milk, lamb and wool) by 6.1% based on average annual returns. Data for each Statistical Area 2 (SA2) were sourced from ABS Agricultural Census data in three years: FY2010-11, FY2015-16 and FY 2020-21. Each SA2 was treated as a representative farm with four outputs (milk, beef, wool and lamb). The inputs into livestock output included: improved pasture area, water applied to pasture, area of pasture watered, ewes, dairy cows and beef cows. Additional values are included from the ABARES AGSURF database this includes costs of inputs, labour in weeks and capital depreciation. What this means for landholders is that there is a positive return in managing the dung beetle populations on farm to ensure the population is diverse and active year-round. Any seasonal gaps provide an opportunity for increased revenue through the spread of existing beetles or introduction of new species.

- Increased revenues of livestock products (beef, milk, lamb & wool) by 6.1%
- increased plant growth by 13.5%

Understanding the rate of spread of introduced species was critical to guiding program decision-making and for future distribution efforts. Through the employment of a stochastic cellular automata model to predict the historical occupancy and abundance of four introduced dung beetles into the Southwest agricultural region of Western Australia, the species spread was estimated. The model predicted optimal species spread in 6-month time intervals for *Euoniticellus intermedius*, *Onitis alexis*, *Onthophagus binodis* and *O. taurus* for the first 10 years after each species' initial release and found the average rate of spread was 79.2 km/year (*E. intermedius*), 35 km/year (*O. alexis*), 30.4 km/year (*O. binodis*) and 27.7 km/year (*O. taurus*). These findings provide a better understanding of the potential spread patterns of dung beetles and a general observation backed by anecdotal reports is that the smaller species are more mobile than the larger species. The model can be used to inform stakeholders, guide agricultural management practices and economic evaluations of biocontrol programs.

The spread of dung beetles across the grazing landscape, will impact on biodiversity within the natural ecosystem. There are numerous components of biodiversity, with early ecosystem function research focussing on the role that species richness plays in driving a single ecosystem function. In general, positive, asymptotic relationships have been reported, indicating functional redundancy with increased species richness. However, recent research is now indicating that a broader view of the biodiversity-ecosystem function relationship is possible by assessing additional components of biodiversity and multiple ecosystem functions. Using artificial assemblages of dung beetles, researchers investigated how two overlooked components of biodiversity (density and species evenness) influence the performance of multiple ecosystem functions (dung removal, dung moisture content, plant shoot growth and plant root growth). The results found that dung beetles increased all ecosystem functions measured. Additionally, the density and evenness of the dung beetle assemblage increased dung removal, dung moisture content and plant shoot growth. These results indicate the value that dung beetles provide to agroecosystems, and the need to consider multiple metrics and functions when conducting biodiversity-ecosystem function research.

The social benefit of most value derived from dung beetles is a reduction in bushflies or black house flies. Researchers conducted experiments with the aim of quantifying the impact of dung beetles on bushfly reproduction. However, the experiments did not return useable data due to insufficient emergence of fly offspring.

4.5 Selection, importation, release, mass rearing and distribution of new dung beetles

The DBEE project was focused on selecting dung beetles to fill the spring gap in southern Australia. Selecting suitable dung beetle species was based on their traits, including:

- High dung burial capacity, especially of cattle and sheep dung – to remove dung from the soil surface to provide increased pasture productivity benefits and reduce breeding opportunities for bushflies and buffalo flies;
- Right seasonal activity, to fill the 'gap' in dung beetle activity;
- Distribution in a similar climate in country of origin;
- Abundance in field. Dung beetles have declined in many countries in the past decades due to the use of chemicals and change of farming practices. Once common, some beetles are now rare and would be difficult to source. Only locally abundant beetle species should be considered;
- Ease of rearing, to allow the quickest mass rearing of new dung beetle species. Note that many dung beetle species have complex breeding and parental care, which complicates mass rearing; and
- Potential competition with current established species or native species.

The following criteria were also considered:

- Administrative requirements to collect/collaborate that can be fulfilled in country of origin;
- Presence of facilities and available expertise in country of origin to assess the potential of dung beetle species or the possibility of exporting species to an intermediate country (e.g. France); and
- Capability to export dung beetles to Australia.

Expert opinions contributed directly to selecting the species targeted in this project. Information available in the literature was used to determine distribution and seasonality of each species. Dung beetle species that did not match the late winter/spring gap were eliminated from the selection process.

The importation of dung beetles in Australia is a two-stage process that falls under two federal departments:

1. An application for new dung beetle species to be added to the Live Import List needs to be submitted through the Department of Climate Change, Energy, the Environment and Water (DCCEEW), which include a public consultation period;
2. An import and release permit needs to be obtained through the Department of Agriculture, Fisheries and Forestry (DAFF).

O. vacca was already included on the Live Import List, and therefore the first step was already completed. A first import and release permit was obtained in March 2018. A second one was obtained in January 2019 to allow for a second year of importation.

New species selected and imported:

- *O. vacca* (Moroccan strain)
- *O. m. andalusicus*
- *G. sturmi*

For the other three species selected (*Onthophagus marginalis subsp. andalusicus*, *Euonthophagus crocatus* and *Gymnopleurus sturmi*), the applications for amending the Live Import List and to receive an import permit were completed simultaneously and submitted in December 2018. The public consultation period ended in April 2019 and a two-year import permit was received in March 2020. The entire process, from submitting the application to amend the Live Animal Import List to receiving the import and release permit, took 15 months. A second import permit was obtained in January 2022 and will be valid for the remainder of the project.

There were two different options considered for the third species: *G. sturmi* and *E. crocatus*. Research from the Moroccan team showed that both species are abundant in spring in Morocco. However, *E. crocatus* is a tunneler and *G. sturmi* is a roller. *G. sturmi* individuals also aggregate on the dung, trampling it in the process which likely prevents dung breeding flies from laying their eggs. In 2018 and 2019, there was no success in breeding *E. crocatus* in France and Morocco, while there was moderate success with *G. sturmi*. It was therefore decided to focus on the latter species as the third for the project. Nevertheless, 240 *E. crocatus* were received in Australia in 2022 and a few beetles were produced (making this the fourth species imported by the project). No further work was done on *E. crocatus*, however, if the need arises, there is now a rearing protocol developed for this species.

Mass rearing activities conducted year-round in climate-controlled environments is a low-risk, highly effective but labour intensive approach to rapidly building numbers for field release.

Once beetles were released from quarantine, they were reared in suitable facilities to build up numbers. The George Bornemissza Mass Rearing Facility established for this purpose on the CSU campus comprised a suite of laboratory facilities such as controlled environment chambers, work areas, walk-in freezer for storage of dung, as well as walk-in mesh houses and field nurseries. This mix of complementary facilities mirrored broadly the long-running successful infrastructure at CSIRO Black Mountain site Canberra. Generally, the laboratory-based rearing in which environmental conditions could be manipulated proved to be most effective because it allowed rearing to take place year-round. In the case of *O. vacca* for example, laboratory work with the imported Moroccan strain allowed at least two generation per year by placing adults under ideal conditions (especially temperature) for breeding and the subsequent growth and development of progeny. The adults from such a round of rearing were then subjected to a 20-week-long protocol to simulate field-overwintering after which they were physiologically primed to breed again.

The major mass rearing efforts were directed at the three exotic species that the project aimed to introduced. These were received by rearing partners from CSIRO's post-importation quarantine facility in Canberra.

- Species 1 (*Onthophagus vacca* – Moroccan strain) was reared chiefly as a hybrid with the previous French strain of this species.
- Species 2 (*Onthophagus m. andalusicus*)
- Species 3 (*Gymnopleurus sturmi*)

These rearing activities complemented by rearing of the French strain of *O. vacca*, and *Bubas bubalus* that were already in Australia.

A grand total of 14,109 beetles were released from mass rearing to the field, mostly in nursery set-ups managed by landholders. The bulk of these were *O. vacca* with lower numbers of *B. bubalus*. For Species 2 (*O. m. subsp. andalusicus*) the delay to field collections in Morocco caused by the COVID19 pandemic resulted in a delay in importation to Australia and progress from quarantine to mass rearing. While a more challenging species to rear than its congeneric, *O. vacca*, it was successfully bred through generations in mass rearing. As of early 2023, the project was not in a position to make field releases because the cohort at CSU was completing its laboratory-based overwinter simulation protocol, so they were not physiologically synchronised with field conditions. The stock at CSIRO was also unsuitable for field release.

This issue was apparent to the project team in 2022 in the lead up to the end of project activities in December 2022. Accordingly, a two-pronged strategy was set in place to deal with this issue and the wider issue of maximising value to producers from the cultures of all dung beetles. First, an expression of interest (EoI) process was arranged to identify 'legacy partners' such as farmer groups that would be suitable to receive dung beetles from the project and take over rearing. Second, a proposal was developed and later supported to maintain rearing activities at CSU with a focus on imported species 2 and 3 (*O. m. subsp. andalusicus* and *G. sturmi*).

Experienced rearing partners received the first releases of species 2 & 3 to carry on rearing and distribution, for final release and establishment in their own regions

A project working group considered 42 EoIs in relation to their track record of successful rearing and the suitability of the climate in their location. Two were assigned as 'Tier 1' (Cannibal Creek Landcare and EcoInsects) to be handed beetles in the summer of 2022/2023 and a handful as others selected to receive beetles in Spring 2023. In January 2023, a consignment of 390 *O. vacca* from the CSIRO facility were handed over to Cannibal Creek Landcare (west Gippsland, Victoria). An illustrated fact sheet was prepared for use by legacy partners (Appendix 8.3). This constitutes a distillation of the practical experience of the project team from rearing and field release efforts, and the wider technical review process that led to the review paper.

It is planned to send available stock of *O. m. subsp. andalusicus*, as well as *G. sturmi*, to additional legacy partners in Spring 2023.

A framework for importation of additional exotic dung beetle species was developed and a list of 14 exotic species of particular interest for Australian livestock industries was prepared (Appendix 8.6). Applications to add these species to the Department of Climate Change, Energy, the Environment and Water (DCCEEW) Live Import List were successful. This will pave the way for the future importation of beetles to continue to expand the diversity of dung beetles in Australia, significantly shortening the time required for importation. The collaboration established between the teams in Australia, Morocco and France has matured, staff have been trained and dedicated infrastructure for dung beetle rearing is available in all three countries. However, we note that without ongoing support, this pipeline will weaken as staff move on and facilities are reassigned to other work.

4.6 Other research

Another pest problem that dung beetles influence is gastrointestinal nematodes. *Program NEMSIM: Population simulation model of free-living stages of gastrointestinal nematodes in a pasture ecosystem* was created to simulate the presence, development and survival of free-living stages of gastrointestinal nematodes in dung and movement of third instar (infective) larvae from dung to soil and vegetation. The model studies nematodes from the egg stage through three larval instars (denoted L1, L2 and L3), using weather conditions to estimate development time and survival through the various stages. After reaching the third instar, larvae were allowed to move to soil and vegetation adjacent to a dung pat. A critical output variable in the model is the number of L3 larvae on vegetation because livestock are reinfested by nematodes by consumption of these larvae on vegetation.

The model follows the population of nematodes in a pasture for one year. Each day, a new dung pat is added, and the number of eggs and larval nematodes in each pat are tracked. Because the development rate and survival of nematodes are determined by conditions within a dung pat and generally not external conditions, a sub model is used to predict conditions (e.g. temperature and FMC-faecal moisture content) within a dung pat, based on the prior state and current weather conditions. Further, because conditions within a dung pat can vary substantially from the crust region to the interior of the pat, the dung pats are partitioned into two regions that are tracked separately (in terms of physical conditions as well as the nematode populations).

Finally, the impact of dung beetle activity on the model output (i.e. abundance of L3 larvae on vegetation) was estimated by evaluating a range of changes to dung conditions likely to result from dung beetle activity. Colonisation of dung by dung beetles is known to change dung in two key ways that are likely to impact the success of larval nematodes: 1) shredding of dung will result in decreased FMC as well as increased oxygen levels within a pat, 2) burial of dung will remove a portion of the nematode eggs or larvae from the core of a dung pat. Dung burial obviously results in population reduction in the core, and reduced FMC results in increased mortality of nematode eggs and larvae (and could subsequently impact temperature within a dung pat). Increased oxygenation of dung pats results in increased rate of egg hatch, so dung beetles might actually cause an increase in abundance of nematodes in dung provided the dung pat does not dry out too quickly (conditions likely to occur in the cooler/wetter times of the year). Because there is little information available to predict the impact of dung beetle activity on physical conditions within a dung pat, the model instead examines the impact of changes to FMC and oxygen on the resultant population of L3 larvae on vegetation. This modelling study is currently under development for a publication to be completed in mid-2023.

With the burial of animal dung by beetles, often to considerable depth, questions pertaining to the impact on water quality were asked. To address these concerns a series of experiments that examined leachate through a series of soil columns was initiated. A lysimeter experiment was also conducted with four distinct soil types in soil columns maintained under field conditions over a period of five months in Wagga Wagga NSW. Utilising 48 soil columns for the lysimeter, CSU researchers quantified the impact of a common introduced dung beetle (*Bubas bison*) on water quality after permeation through four different soil types sown to winter annual pastures. Lysimeter columns included the control that had no dung or beetles added and treatments that consisted of columns with i) dung without dung beetles and ii) dung with dung beetles. Dung beetles and soil type impacted on the performance of improved overseeded annual pastures as measured by biomass accumulation over a four-month growing season.

The four soil types, namely, Chromosol, Kandosol, Rudosol, and Vertosol, differed considerably with respect to their water-holding capacity and nutrient profiles, as assessed by initial soil testing and soil leachate evaluation following rainfall plus simulated rainfall events. The concentration of Escherichia coli resulting from cattle dung, cattle dung plus beetles, and the control soils without dung or beetles was assessed in collected leachates over a three-month period. E. coli numbers were significantly increased following B. bison activity, when compared to the dung-only and control treatments. Evaluation of the soil microbiome, by assessing genomic DNA in soils sampled 10 cm below the soil surface where dung beetles remained active following tunnelling, revealed significant differences among soil types with respect to bacterial and fungal communities. Within each soil type, dung beetle activity impacted the fungal community structure, but not the bacterial community. Pasture performance as assessed by biomass accumulation was significantly improved following dung beetle activity in later stages of pasture growth, while E. coli numbers and total coliforms appeared unaffected by beetle presence. The lysimeter work performed here has resulted in a completed publication in the journal Agronomy (2023).

Whilst considering the relationship between dung beetles and gastrointestinal (GI) parasites from an economic perspective, there was an opportunity to also investigate the impact of anthelmintics used to treat GI parasites, on dung beetles. Anthelminthic residues in livestock dung can have non-target effects on dung beetles but specifically, the effect of anthelmintic drugs under various simulated regimes of Targeted-selective-treatment (TST) was tested. Targeted-selective-treatment is a strategy developed to slow anthelmintic resistance in gastrointestinal nematode populations. This treatment strategy involves treating only vulnerable, high-risk animals rather than the entire herd/flock. Up until now, no study has examined the impact of anthelmintic drugs on dung beetles under a TST regime. The controlled glasshouse experiment found high adult dung beetle survival always occurred, but that larval survival was variable, however high larval survival was possible within TST management. By leaving a portion of the herd untreated, TST can provide anthelmintic-free refugia and may reduce the overall impact of anthelmintic treatment on dung beetles.

This research highlights two important management practices that may affect on-farm dung beetle populations. First, by selectively treating only a portion of livestock with anthelmintic, dung beetle populations may be able to capitalize on the anthelmintic-free ‘refugia’ this strategy provides. Second, the effects of anthelmintics on dung beetle populations may be reduced by restricting livestock to a small area post-treatment until such time as the concentration of anthelmintic in the dung has reduced to 125ppb. And there is a third management practice, clear from this research and previous studies: that careful timing of anthelminthic treatment of livestock can reduce impacts on dung beetles. As adults are not affected, but larvae are, farmers should avoid anthelminthic treatments of their livestock during dung beetle breeding months.

5. Conclusion

The DBEE project was a multifaceted project that aimed to expand and enhance dung beetle activity as well as educate producers that dung beetles can improve profitability and productivity across the grazing landscape of southern Australia. Utilising a mixture of field monitoring, field and laboratory experimentation, quarantine, laboratory and field rearing of dung beetles, and economic analysis the project has distributed beetles to new locations; quantified the economic value of dung beetles; and successfully enhanced the knowledge of producers and the broader community of the critical roles dung beetles play.

The project evaluation review assessed project impacts to determine whether useful service were provided to Australian producers, industry, Rural Research and Development Corporations (RDCs), governments and others. The evaluation found that DBEE project undoubtedly delivered nationally coordinated, strategic research that was beyond the reach of any single organisation.

There were several impediments that delayed project progress including extensive challenges around initial contracting, COVID19 pandemic, difficulties around dung beetle rearing and numerous weather-related impacts (floods, tornados, hailstorm, drought, bushfires and subsequent destocking). However, project partners adapted to these challenges by thinking innovatively and working hard to overcome these difficulties.

The three most significant impacts for producers resulting from the DBEE project are:

1. The importation and release of novel dung beetle species to fill the late winter-early spring activity gap in southern Australia
2. The enhanced producer awareness and capacity-building delivered through the training activities and communications and extension arm of the project.
3. The calculation of the economic value of dung beetles at a landscape level.

The importation and mass rearing aspect of the project was responsible for the introduction of two new species to Australia (*G. sturmi,* and *O. m. andalusicus*), the support of two recent introductions (*O. vacca* and *B. bubalus*) and the distribution of other previously introduced species into new regions (*O. caffer, B. bison, G. spiniger, C. hispanus* and other species). The importation activities have strengthened the pathways in dung beetle importation in several ways. First, an additional 14 species have been added to the Live Import List, speeding the process for future introductions, and providing a pool of suitable candidates covering current identified gaps. Second, the project developed rearing protocols for the three newly imported and released species that were shared with partners and used in mass rearing, helping produce beetles to be released on farms. As part of the on-farm producer nursery program, new knowledge was acquired on these species, ensuring releases are more targeted to the appropriate regions and seasons. For example, optimal field conditions for the establishment of *O. vacca* are cool moist environments where *O. taurus* is relatively scarce.

The successful importation of the beetles occurred through a pipeline developed to access beetles from Morocco, via France and processes approved by DAFF for quarantine rearing and release of dung beetles. This pipeline allowed the importation of four new species during this project, three that were given to partners. Thousands of beetles were produced from the small number of beetles received into quarantine, many of which were given to project partners. This international collaboration with research teams in Morocca and France, could contribute to future projects as staff have been trained and dedicated dung beetle infrastructures are established in three countries.

There is an opportunity now to take advantage of this pipeline and plan further introductions from the 14 new species have been added to the Live Import List. Staff and infrastructures will be inevitably reassigned to other areas without further funding and investment in bringing in more species to Australia to fill the service gaps.

With the last of the imported dung beetles still in Quarantine due to delays caused by COVID19, an EoI was released to identify suitable candidates who were willing to continuing rearing activities and had the resources and expertise to do so. The organisations identified in the EoI legacy partner process that will receive beetles from the DBEE project in its final stage constitute a tangible legacy. This addresses the need for pathways to extend the results of rural R&D, since the legacy partners receive breeding stock of beetles, print material on how best to maximise their breeding success after hand-over and technical support. This, in turn, provides further capacity in providing dung beetle services relating to the availability of beetles and associated technical know-how.

Improving producer awareness of dung beetles over the course of the project, the project researchers have engaged closely with livestock producers for workshops, surveys, beetle collections and onward redistribution and collaborative field nursery rearing. One of the key messages that the workshops and online forums has introduced to producers and land managers, is that “dung beetles” are not one species actively processing dung all year, but a successful population is multi-species covering different times of the year. The interactive workshops focussed on beetle identification, monitoring and surveillance, rearing and management. These were incredibly well-received and demand for these workshops was beyond what could be delivered, demonstrating the interest in dung beetles from producers and the community. Field days/workshops frequently attracted over 30 people, when normal attendance at these sorts of events is 10–15 people; this demonstrates the enthusiasm the community had for learning about dung beetles. The workshops appeared to be an excellent format to engage directly with primary producers which will continue through the network of advocates and enthusiasts cultivated by the project. The project has developed novel educational tools in the form of pocket identification guides, electronic identification resources, videos, worksheets, and information on dung beetle distribution and purchasing which continue to be available to support producers and collaborators.

The project has forged ongoing collaborations between land management organisations, commercial dung beetle providers and researchers that will continue to share knowledge and build capacity in dung beetle delivery. Approximately 40–50 Landcare groups, Catchment Management Groups and farming systems groups across NSW, Victoria, Tasmania, SA and WA were involved in the project over its duration. The project has brought together geographically dispersed organisations that will facilitate expansion of the dung beetle redistribution network across southern Australia. For example, developing relationships with land management groups to harvest and relocate relevant beetles for their region but also local producers have developed the confidence and expertise to take on the role of farmer mentor for a region. The project has also built considerable research expertise in dung beetles through the training of several PhD students. This capacity building is critical to continuing to build on the successes of the project.

Since the commencement of the DBEE project there has been an increase in private enterprise in the dung beetle space. While anecdotal, commercial providers have reportedly commented on increased business since the project website was developed. In 2020, commercial supplier SoilCam was quoted in a Queensland Country Life article saying that orders were increasing all the time as more farmers are becoming aware of the benefits of dung beetles. Project website metrics show that the “buying dung beetles” page has the highest number of page visits after the home page.

As more producers and land management groups understand the economic value of dung beetles, they can make informed management decisions on their operation and investments. Results of experiments have shown increased ecosystem functions such as dung beetles generated an 47% reduction in dung on the soil surface, which reduces pasture fouling and increases pasture availability. In addition to the increase in pasture availability, significant improvements in pasture growth were noted at two of three locations in the Riverina (NSW) but not across all experiment sites. Economic analysis of dung beetles has shown that in SW WA, livestock stocking rates increased, and across southern Australia (excluding SA) revenue from all livestock products increased by 6.1%. The average annual total revenue value of dung beetles over the 10 years from 2011-2021 is $619 million. Insufficient diversity and/or abundance of dung beetles means suboptimal ecosystem services provision in that area. There is a positive return in managing dung beetle populations to ensure it is diverse and active year-round.

Managing dung beetle populations across a wider area demonstrates to the broader community audience how red meat industry utilises best practices to maximise productivity while protecting the environment. An on-farm dung beetle management guide is in the final stages of development and expected to be available for producers by mid-2023. This guide will bring together the practical knowledge producers require to make decisions for their operations including drench management. Research on the impact of anthelmintics of dung beetles under a targeted-selective-treatment approach highlights management practices that may affect on-farm dung beetle populations. First, by selectively treating only a portion of livestock with anthelmintic, dung beetle populations may be able to capitalize on the anthelmintic-free 'refugia' dung. Second, the effects of anthelmintics on dung beetle populations may be reduced by restricting livestock to a small area post-treatment until such time as the concentration of anthelmintic in the dung has reduced. There is a third management practice, clear from this research and previous studies: that careful timing of anthelminthic treatment of livestock can reduce impacts on dung beetles. As adults are not affected, but larvae are, farmers should avoid anthelminthic treatments of their livestock during dung beetle breeding months.

The combination of the field monitoring and experimental data collated in Dashboard 2.0 website, allows prediction of dung burial and benefits over southern Australia. Demonstrating these benefits with Australian beetles under Australian conditions will be useful for future communication and outreach activities to better demonstrate to land managers the ecosystem services provided by dung beetles.

5.1 Key findings

- The field experiments found positive or neutral effects of beetles on dung burial and by association pasture fouling (reduction of 48%), soil nutrients (no effect on N, increase in P, and mixed results for K) and pasture growth (up to 13%).
- The quantified estimates of the economic value of dung beetles for farmers were generated using two approaches: historical and present. Both approaches show dung beetles have a significant positive effect on economic value. The approach for historical value for south-west WA found that dung beetles increased livestock stocking rates. The approach for present value across southern Australia found that dung beetles increased revenues from all livestock products (beef, milk, lamb and wool) by 6.1%.

- Importation of four novel dung beetle species to fill the late winter-early spring activity gap in southern Australia.
- Expansion of the range of existing exotic species.
- Enhanced producer awareness and capacity-building delivered through communications and extension activities.
- The curated data from the monitoring program is one of the largest databases of dung beetle presence and abundance in the world. This is important information for producers that will allow them to understand which dung beetle species are present/active when and where to be able to tailor their land management practices to relevant species.
- The intensive field experiments conducted across WA, NSW, New Zealand and Victoria comprise the largest field experiment undertaken for the purpose of quantifying the benefits of dung beetles in the Australian context. Together with the economic quantification developed in the project, these findings demonstrate to farmers the benefits that dung beetles can provide and will hopefully encourage land managers to actively manage their local beetle populations to improve on-farm productivity.
- The project has forged ongoing collaborations between land management organisations, commercial dung beetle providers and researchers that will continue to share knowledge and build capacity in dung beetle delivery.
- Mass-rearing facilities have been established at several sites across Australia and project partners have developed a much greater understanding of mass-rearing requirements for multiple dung beetle species.
- Anecdotally, the DBEE project has led to increased demand for commercial dung beetle services.

5.2 Benefits to industry

The introduction of three new spring active species means that for first time producers have dung beetles processing dung across a large proportion of pasture system in southern Australia at this time. Potentially it may take decades for these species to establish across their maximum range but the benefits on farm are immediate and across the industry are cumulative.

The same applies to successfully expanding of the range of existing exotic species to ensure optimal ecosystem services provided by dung beetles on farm. Ongoing support and land management collaborations will increase the chance of success with purposeful cropping and redistribution.

The project has forged a network between land management organisations, commercial dung beetle providers and researchers that will continue to share knowledge and build capacity in dung beetle delivery. Quantification of the benefits and explanation of these to producers at a regional and local level has been critical to management decisions on farm. Utilising the tools and material developed by the project land managers are able to benefit from dung beetles direct and immediate value.

In many ways the monitoring program undertaken has highlighted the gaps at a regional and landscape level down to a farm level and provides a blueprint for what can happen next for either an individual producer or land management group (e.g. what species should be in the region). Raising producer awareness of dung beetles through workshops and monitoring programs benefits not just the immediate farm but the wider community and environment. This project showed that producers that became engaged in the monitoring process, often continued to monitor across their property and had them questioning livestock management practices particularly in terms of drench management.

6. Future research and recommendations

1. *Extension program:* In the regions that have not benefited from any of the projects and programs in the past decade, significant promotion of the ecosystem services and value of dung beetles to livestock producers is still required via a comprehensive extension program. There continue to be regions and producers who do not understand the benefits that dung beetles can provide in pest management and the value they bring to a grazing system. Central and Northern Qld and the Northern regions of WA need a program of extension that involves the development of material that is specifically relevant to their extensive systems.
2. *Geographic and seasonal gaps:* The benefits provided by dung beetles are assumed to be available to varying degrees in each locality that has dung beetles. Therefore, a lack of dung beetles to provide those benefits represents an opportunity cost to farmers, the industry and the broader community. There are many geographical gaps across Australia where insufficient diversity and/or abundance of dung beetles are not providing optimal ecosystem services. This can be divided into areas where:
    - there are species that are known to fit a gap but are not present due to a range of reasons such as geographical barriers to spread or harmful on-farm practices. Supplying a combination of different beetle species and the education required to ensure the action is successful is perhaps the lowest hanging fruit for any future funding into this area. There is already a combination of commercial and NGO groups active in this space, and although funding has been scarce, the concept has generally been boosted by the growing interest in ideas such as regenerative farming and soil carbon.
    - there are species that are present elsewhere in Australia that may be able to fit a gap, but they have not been tested/evaluated before. This is a more complex are and requires the assistance of technical experts.
        - Using a trap and relocate method, species of beetle that have adapted to regions outside previously known sightings could potentially be relocated to similar climatic and geographic regions.
        - New climate mapping of potential dung beetle distribution is needed to ensure the most successful outcomes from this relocation approach. Many of the tools available on dung beetle dispersal are based on climate mapping completed in early 2000s and updating these to reflect changes to our climate would provide an impetus for understanding where the beetles could establish.
    - there are no species that are available in Australia that fit a gap. This is most likely because the gap falls into a region of unsuitable climate or soil types for currently available beetles. This ecosystem service gaps can only be filled by the careful selection, importation, rearing and establishment of a new species.

- The cost and resources of successfully bringing in a new species are estimated to be in excess of $2m over five years. However, it should be noted that concurrently bringing in multiple species does not exponentially increase these costs. Therefore, the most efficient and successful model is likely to be the development of a pipeline program with committed funding over 8–10 years.
- The funding of a continuing pipeline of new dung beetle species to fill the ecoservice gaps across the Australian farming landscape has been estimated to provide the largest potential benefit for the livestock industries and the authors also consider this the highest priority.

3. *Management of livestock and dung beetles:* Producers want specific and practical information packages on dung beetle management in relation to the use of animal health and pesticidal products. The key information providers on the best-practice use of pesticides in the livestock industries have limited available information on dung beetles, and in particular, how to include dung beetles into a holistic IPM strategy. Further research trials are needed particularly with management of anthelmintics and the use of a Targeted-selective-treatment strategy for treating herds/flocks.

7. References

Edwards, P (2007) Introduced Dung Beetles in Australia 1967-2007: current status and future directions

Wright, J, Gleeson, P and Robinson, F (2015) MLA Project B.ERM.0213: Importation and rearing of 2 winter - spring active dung beetles for southern Australia

8. Appendix

8.1 Project media, communication and extension

8.1.1 Featured Media

2GB SYDNEY 12 JAN. 2023 National Rural News 2GB	RN 02 JAN. 2023 Why we need dung beetles Max Walden, Producer. Guest…	The Canberra Times 26 DEC. 2022 Why one group spent five years in cow dung Liv Casben (Canberrra Times)
ABC Rural 13 DEC. 2022 Gippsland farmers get their hands dirty to manage dung Peter Somerville (ABC Rural)	THE CONVERSATION 23 NOV. 2022 They might not have a spine, but invertebrates are… The Conversation	farmonline NATIONAL 24 MAY. 2022 Red meat industry welcomes newest (and smallest) engineers Kristin Murdock
ABC 17 MAY. 2022 CSIRO imports African dung beetles to help Aussie farmers ABC	The Daily Advertiser 12 MAY. 2022 Moroccan dung beetles prepared to clear poo from… Monty Jacka	NEWS BREAKFAST 11 MAY. 2022 ABC 1 Sydney - News Breakfast ABC 1 Sydney, News Breakfast
GIZMODO AU 11 MAY. 2022 Australia Is So Full of Sh#t We've Had to Import Dung Beetles Zachariah Kelly	The West Australian 11 MAY. 2022 Foreign dung beetles to improve local soil Liv Casben | AAP	le Desk 10 MAY. 2022 Dung Beetles from Morocco shipped to Australia to… La Redaction (Morocco)

The Canberra Times 10 MAY. 2022 **CSIRO imports dung beetles to help clear paddocks of poo…** Alex Crowe	Charles Sturt University 10 MAY. 2022 **Beetles with benefits for Australian ecosystems and farmers** Charles Sturt University	mla MEAT & LIVESTOCK AUSTRALIA 05 MAY. 2022 **New dung beetle species on Australian soil** Meat & Livestock…
THE NATIONAL TRIBUNE 04 MAY. 2022 **New dung beetle species on Australian soil** The National Tribune	16 FEB. 2022 **Crop study assesses dung beetle numbers** Farm Weekly	The Border Mail 27 JAN. 2022 **Thrilling discovery for Jill Coghlan** The Border Mail
MIRAGE news 12 JAN. 2022 **Dung beetles: workers worth looking after** Mirage News	07 JAN. 2022 **Dung beetle team on a roll at UWA** Farm Weekly	6PR882 NEWS TALK 23 NOV. 2021 **The dung beetle crisis explained** 6PR882 News Talk
mla MEAT & LIVESTOCK AUSTRALIA 16 NOV. 2021 **How dung beetles can improve herd health** Meat and Livestock Australia	ABC 31 OCT. 2021 **When the COVID-19 pandemic hit…** ABC Radio (Canberra)	ABC 22 SEP. 2021 **Dr Russ Barrow from Charles Sturt…** ABC Radio (Australia)

22 SEP. 2021 **The latest dung beetles to be…** Flow News 24	21 SEP. 2021 **Careful dung beetle management will…** Jennifer Nichols (ABC Rural)	12 SEP. 2021 **Researchers welcome Moroccan natives who may change…** About Regional
09 SEP. 2021 **Dung beetle FAQs: ask expert** Mirage News	18 JUN. 2021 **Interview with Dr Valerie Caron** ABC Perth	11 JUN. 2021 **Dung beetles with benefits** CSIROscope
15 APR. 2021 **Interview with Dr Russell Barrow** ABC Goulburn Murray	11 MAR. 2021 **Discover benefits of Dung Beetles for your property** Mirage News	11 MAR. 2021 **Dung beetle field day coming to South Gippsland** Sentinel-Times
22 JAN. 2021 **Solving the great Australian poop problem** Particle	11 JAN. 2021 **Why flies are particularly annoying this summer** The University of Western…	24 NOV. 2020 **Dung beetles first on agenda in campaign to improve soil** The Land

17 NOV. 2020 **The world of dung beetles** Busselton-Dunsborough Mail	07 NOV. 2020 **Loving the Land | Where have all the dung beetles gone?** The Border Mail	23 OCT. 2020 **New dung beetle species set...** ABC Rural
22 OCT. 2020 **High hopes for French dung beetle** ABC Rural	15 OCT. 2020 **Beetles set to get our pastures out of the crap** North Queensland Register	03 OCT. 2020 **UNE dung beetle project in North West, Northern...** The Northern Daily Leader
06 SEP. 2020 **Dung beetle count shows benefits** Stock Journal	16 AUG. 2020 **Dung beetle monitoring key to Beetles with Benefits...** The Northern Daily Leader	30 JUL. 2020 **Keeping an eye on beneficial beetles** Farming Ahead

8.1.2 Project, media and communications material

Nature of materials / activities	**Number**	**Details** (Please provide details if appropriate (eg links to publicly available documents)
Press releases	6	3/5/2022 G. sturmi importation - New dung beetle species on Australian soil | Mirage News - New dung beetle species on Australian soil (phys.org) - New dung beetle species on Australian soil - Verve times - New dung beetle species on Australian soil | Meat & Livestock Australia (mla.com.au) - New dung beetle species on Australian soil - swifttelecast - New dung beetle species on Australian soil (knowledia.com) - 1630931139.pdf (isentia.com)

		27 Apr. 2020: Dung Beetle project success flies in the face of COVID-19 **23 Jun. 2020**: Dung beetle field guide now available to primary producers **12 Sep. 2020:** Milestone achievement as new dung beetle species importation trumps international COVID logistical challenges. **4 Sep. 2019:** DBEE Breeding Success https://www.dungbeetles.com.au/media-releases **20 Dec. 2019** - NZ - Press release on Dec 2019 mass releases of dung beetles on Mahia Peninsula. Created by Hawke's Bay Regional Council and reproduced here on the Whangawehi Catchment Group website. https://whangawehi.com/2019/12/20/new-farm-workers-in-mahia/
Media appearances – press and TV	731	Radio interview with ABC Radio Science – Robyn Williams – pre-recorded on August 9th 2022 - ABC Wide Bay - 30 Aug 2022 09:14:18 (meltwater.com) Video – ABC The BrightSide Bites - CSIRO imports African dung beetles to help Aussie farmers - ABC News 11/05/2022 CSIRO TV Interview- ABC News Breakfast 11/05/2022 CSIRO TV Interview – WIN News 11/05/2022 CSIRO Radio interview – ABC Canberra Afternoons with Georgia Stynes 09/05/2022 Interview with Liv Casben Australia Associated Press Final species arrives for dung beetle project | The SE Voice 06/05/2022 Interview on phone with Alex Crow for Canberra Times CSIRO imports dung beetles to help clear paddocks of poo problem | The Canberra Times | Canberra, ACT 06/12/21 Interview for the Countryman on November 26th Article in the Countryman on Dung beetles provide millions in benefits to WA farms and could stop the need to drench livestock | Countryman 2/12/21 Countryman and 7 syndicated papers (Kurz event) - https://www.countryman.com.au/countryman/in-pictures-digging-for-dung-beetles-at-donnybrook-on-farm-field-day-ng-b882062112z 31/10/21 Article in ABC (following interview on 03/09/21 and talked to journalist on 29th) https://www.abc.net.au/news/2021-10-31/dung-beetle-research-in-the-time-of- covid/100570386 15/09/21 Radio interview - FLOW FM with Rikki Lambert - https://www.spreaker.com/episode/46525389 03/09/21 Radio interview - ABC Canberra - CSIRO research shows beetles can battle blowflies! - Saturday Breakfast - ABC Radio 6/7/2021 Radio interview - Lost in Science community radio (for Melbourne and about 25 regional areas) - Part 1 - https://www.3cr.org.au/lostinscience/episode-202107150830/its-bs-episode-dung-beetles-and-difficult-physicists - Part 2- The pre-birth song of the masked Lapwing, and the return of the dung beetle! | 3CR Community Radio

		15/06/2021 Radio interview - ABC Perth Interview with Christine Layton (WA Afternoons) on G. sturmi arrival 24/2/2021 Radio interview – dung beetles – ABC radio Canberra with Georgia Stynes https://www.abc.net.au/radio/canberra/programs/afternoons/dung-beetles-research-habitat-role-biological-control/13184362 15/10/20 Radio interview – Drive Jim Wilson Manjimup-Bridgetown Times (Northcliffe event) - https://www.countryman.com.au/countryman/dung-beetles-provide-millions-in-benefits-to-wa-farms-and-could-stop-the-need-to-drench-livestock-ng-b882062337z 18/10/19 - Linked activity – Doug Pow is a local dung beetle champion and recognized in the WA Landcare Awards 2019 https://www.abc.net.au/news/rural/2019-10-18/wa-farmer-uses-beetles-and-charcoal-to-combat-climate-change/11613846 http://www.futuredirections.org.au/publication/doug-pow-dung-beetles-eco-engineers/ 5/9/2019 – radio interview with Camille Smith newsmedia.com.au 4/12/2019 – interview with Bairnsdale newspaper reporter Lyric Anderson. 18/12/19 ABC south west Rural Report (radio) interview, aired on local radio, WA Country Hour and (excerpt) in regional news. Reporter Jon Daly visited monitoring site and observed trap setup and demonstration trap clearance. Interviewed Kathy Dawson and farmer Peter Mason. https://www.abc.net.au/radio/southwestwa/programs/rural-report/great-southern-and-south-west-rural-report/11791328 https://www.facebook.com/abcsouthwest/photos/pcb.10156639647651811/10156639641891811/?type=3&theater (157 Likes, 127 comments, 13 shares) 13/1/20 "Drought decimating dung beetles" – syndicated to: • **North QLD Register - https://www.northqueenslandregister.com.au/story/6569128/drought-decimating-dung-beetles/?cs=4770** • **Farm Online - https://www.farmonline.com.au/story/6569128/drought-decimating-dung-beetles/** • **The Land - https://www.theland.com.au/story/6578443/drought-decimating-dung-beetles/?cs=4941** • **Good Fruit & Vegetables - https://www.goodfruitandvegetables.com.au/story/6569128/drought-decimating-dung-beetles/** ABC Central West: Radio interview file NA **MLA Friday Feedback – Busy dung beetles Nov 2019** **The Weekly Times - https://www.weeklytimesnow.com.au/subscribe/news/1/?sourceCode=WTWEB_WRE170_a_GGL&dest=https%3A%2F%2Fwww.weeklytimesnow.com.au%2Fagribusiness%2Ffarm-magazine%2Ffrom-renowned-cattle-breeding-operator-to-dung-beetle-expert%2Fnews-story%2F64cf2367e46b937700673ff0e44766e6&memtype=anonymou**

		s&mode=premium Nov 2019 - NSW Farmers - https://www.nswfarmers.org.au/NSWFA/Posts/The_Farmer/Innovation/Turning_80_million_tonnes_of_livestock_dung_into_farming_profits.aspx 30/9/19 - Charles Sturt University - https://news.csu.edu.au/latest-news/charles-sturt-celebrates-milestone-in-national-dung-beetle-research 11/10/19 Meat and Livestock Australia - https://www.mla.com.au/news-and-events/industry-news/new-dung-beetles-rolling-through/ 4/10/19 - Sheep Central - https://www.sheepcentral.com/biochar-sheep-beef-and-crop-options-to-feature-in-two-state-tour/ 2/10/19 - The Advocate - Dung beetles on the rise across southern Australia https://www.theadvocate.com.au/story/6418853/harnessing-the-power-of-exotic-dung-beetles/?cspt=1574143777|d24e4782ed2651649f76065fb3bfdca6 27/9/19 Nine News Riverina – "Beetle Juice" Prime7 News Wagga: Studio read with no video on file Sep 2019 ABC Evenings with Chris Bath 15/4/20 - ABC Weekend Breakfast with Leslie Weston & Lucinda Corrigan 6/9/19 - Charles Sturt University https://news.csu.edu.au/latest-news/researchers-on-cusp-of-success-as-they-await-the-birth-of-6000-baby-dung-beetles syndicated to Beef Central Spring 2019 - Ingrain Magazine "Digging deep with dung beetles" https://www.dropbox.com/s/bbll6kt7t8td7hq/Ingrain-magazine-vol1-no4-spring-2019.pdf?dl=0 17/6/19 - The Rural https://www.therural.com.au/story/6221126/recognition-of-dung-beetles/
Brochures, fact sheets, posters and newsletters	41	Regional dung beetle guide for Riverina NSW, East Gippsland Vic, North West NSW, Northern Agricultural Region WA, Northern Tablelands NSW, South West Victoria, Tasmania https://www.dungbeetles.com.au/regional-id-guides Booklets for producer events, individually designed to meet local needs x5 Produces booklets for MIG's monitoring site producers Newsletter article for the UWA Institute of Agriculture December 2021 Newsletter UWA0112-IOA-Newsletter-December-2021.pdf Southern Farming Systems E newsletter articles –21.10.2021, and 26.10.2021 Southern Forests Community Landcare Newsletter (mailchimp) DBEE Newsletters • 20/05/2021 - Dung Beetles | On The Ground – May 2021

		• 23/12/2020 - Happy Holidays | December 2020 • 07/12/2020 - Dung Beetles | On The Ground – November 2020 • 24/09/2020 - Dung Beetles | On The Ground – September 2020 • 25/06/2020 - Dung Beetles | On The Ground – June 2020 • 15/04/2020 - COVID-19 update | DBEE | Dung Beetle Ecosystem Engineers • 13/12/2019 - Dung Beetles | On The Ground – December 2019 • 20/09/2019 - Dung Beetles | On The Ground – September 2019 • 23/07/2019 - Dung Beetles | On The Ground – July 2019 • 11/04/2019 - On The Ground April 2019: Follow the project that's populating southern Australia with dung beetles. Newsletter for Fitzgerald Biosphere Group Aug 2020 Newsletter for WCC Nov 2020 Newsletter for WCC Feb 2021 Information booklet for WCC producers Fowler, S. and Weston, P. What is the effect of dung beetles on gastrointestinal nematodes of stock? https://www.dungbeetles.com.au/technical-reports Fact sheets on E. fulvus, O. taurus, G. spiniger, B. bison, O.binodis & O.australis have been produced by AgVic and distributed to farmer groups. Feature articles in the FarmLink quarterly magazine based on information provided by DBEE and a technical report written in the FarmLink Research Report 2020. Newsletter articles in the SFS fortnightly E-News Update – 5 editions Gippsland DBEE E- Newsletter monthly editions – 4 editions Gippsland results (species ID (informal project officer ID) and locations) info page x1 - contained within 2020 Agricultural Research Results Booklet Expressions of interest for producer run monitoring sites was distributed as a newsletter through the Landcare network and as a classified ad in the North West Magazine (NSW) DBEE news is regularly updated to recipients of a Farming Network Newsletter in SW WA (distribution ~500 south west farmers) emailed approximately twice/month. South West Prime Lamb Group - Bindi Hunter, Agriculture Victoria has produced a fact sheet about the monitoring sites being run by SWPLG **Brochures DBEE – Project overview** (PDF) & **DBEE – Get involved** (PDF) **Fact sheets/protocols available on website** **What dung beetle is that?** **Dung beetle sampling guide** **Rapid floatation sampling** **Dung preparation guide** **FAQs**

		FAQ page **Posters - DBEE themes, George Bornesmissza, ID book overview, MyDungBeetle Reporter app**
Web page	2	https://www.dungbeetles.com.au/ DBEE monitoring results dashboard and prediction tool: https://dungbeetles.shinyapps.io/dungbeetlemaps/
Field days, expos, field walks	42	30/11/22 - South Highlands, NSW - Southern Highlands Landcare Network, Bowral, NSW (Interaction 22) 17/11/22 - Wrattonbully, SA - Limestone Coast Landscape Board, SA (Interaction 20) 16/11/22 - Woolumbool, SA - Limestone Coast Landscape Board, SA (Interaction 14) 15/11/22 - Mt Gambier, SA - Limestone Coast Landscape Board, SA (Interaction 23) 25/10/22 - Bergalia, NSW - property of Peter & Mary Atkinson in Bergalia. SE LLS (Contact Kevin Dibley) (Interaction 12) 20-22/9/22 - Henty, NSW - Henty Field Days (Interaction 750) 24/3/22 - Portland Region, Vic - Cashmore Park, Southwest Prime Land Group (Interaction 26) 3/3/22 - Fish Creek, Vic - South Gippsland Landcare Network, Bass Coast Landcare Network (Interaction 48) 17/2/22 - Caragabal, NSW - Caragabal West, Central West Local Land Services field day (interaction 22) 16/2/22 - Narromine region, NSW - Central West Local Land Services / Willydah field day (interaction 24) 15/2/22 - Tooraweenah, NSW - Emu Logic, Central West Local Land Services field day (interaction 32) 6/11/21 - Dung Beetle Field Day at SFS Research Trial Site Inverleigh (Vic) Estimate 50 people 5/11/21 - Dung Beetle School Visits, Launceston (Tas) Estimate 25 people 3/11/21 - Spring Field Day, Cressy (Tas) Estimate 30 people 25/9/21 to 2/10/21 - Perth Royal Show – interactive display, specimens, videos, posters, children's activity station – engaged +4000 people 24/6/21 (The MacKillop Group) Struan, SA - One whole-day workshop presented at Struan in SE-SA, for monitoring collaborators and others 28/5/21 (Central Tablelands Landcare) Kelso Public School, Kelso NSW - Address given and dung beetle trial set up 26/5/21 (Central Tablelands Landcare) Orange Anglican Grammar School, Orange NSW – Address given and dung beetle trial set up 25/5/21 (Mid Lachlan Landcare) - Workshop at Neville, NSW and an additional field visit conducted in the Orange region of NSW

		25/5/21 (Mid Lachlan Landcare) field excursion and set up B. bison field nurseries near Neville NSW: 12 nurseries were set up 6/5/21 – Western Dairy - Dairy Innovation Day annual on-farm conference and exhibition – display booth 26/3/21 Wairewa, Vic - Far East Victoria Landcare / Greenlands: workshop / field day Attendees 15 25/3/21 Bengworden, Vic - SFS. Topsoils Project and East Gippsland Landcare Network/Meroka: workshop / field day Attendees 25 24/3/21 Toora, Vic - South Gippsland Landcare Network: workshop / field day/ O. taurus, E. fulvus Attendees 45 23/3/21 Labertouche, Vic - Westernport Catchment Landcare Network: workshop / field day/ A. fimetarius, O. taurus, H. arator Attendees 52 22/3/21 Chintin, Vic - Macedon Ranges Shire Council, Port Phillip and Westernport CMA: workshop / field day/ A. fimetarius, O. taurus, H. arator Attendees 40 18/3/21 Holbrook NSW – Blairgowrie, Holbrook Landcare Network: workshop / field day Attendees 22 6/3/2021: field visit as part of Rural Solutions SA workshop 12 attendees 5/3/21: The Grassland Society of Southern Australia – Limestone Coast Branch 'Gearing Up for the Season' field day (included workshop presentation). Ben Stark's 753 Old Kingston Rd, Stewart Range; 40 attendees 26/11/20 Tamworth field day in association with Tamworth Regional Landcare Association 23/11/20 – Virtual Field Day with Gippsland Agricultural Group Gippsland (COVID 19 restrictions) – video hosted on website https://vimeo.com/showcase/7833102/video/482885711 18/9/20 - Agricultural Research Info Day with Scotch Oakburn College Tasmania involving 14 students 30/7/20 – Trial Site Update Field Day (inc. discussion on DBEE Project) Tasmania involving 70 farmers 28/7/20 Gunning, NSW - Tableland Farming Systems: field day / seminar Attendees 44 30/10/19 - Dung Beetle Ecosystem Engineers Project information presentation at the Southern Farming Systems Spring Field Day held in Tasmania, with 30 attendees. SA - Promotion of the project at on field day and two crop walks – Avenue Range, Sherwood and Keith. Oct 2019 - SW Vic - Discussion of project when site visited as part of the National Biochar tour. About 80 attendees West Midlands Group, Dandaragan WA - Presented information about DBEE, especially beetle monitoring, field experiments, and beetle distribution Rangelands NRM, Dongara, WA - Presented information about DBEE, especially beetle monitoring, field experiments, and beetle distribution

		16/10/19 - Southern Farming Systems marquee display with Russ Barrow (CSU) presenting three information sessions about the Dung Beetle Ecosystem Engineers Project, at the annual AgriFocus event held near Geelong, with approximately 250 attendees at the event. 7/10/19 Western Beef – on-farm presentation and field walk (Manjimup WA). Host Doug Pow 8/7/19 Collie WA - co-hosted by Leschenault Catchment Council; field walk host Peter Piavanini https://www.colliemail.com.au/story/6248525/special-event-in-collie-for-local-farmers/
Stakeholder forums, meetings, presentations, workshops, webinars	116	26/10/22 Workshop - Berry, NSW - Berry Landcare and NSW LLS (Ed Hoagn local contact) (Interaction 10) 25/10/22 Webinar - - Dung Beetles in SE Australia (coordinator Karen O'Keefe) (Interaction 24) 22/6/22 Seminar - - Gippsland Farmes Group / Southern Farming Systems (Interaction 40) April 2022, presentation to the Mt Barker Ag Bureau, dung beetles and biochar 23/3/22 Workshop - Rossbridge, Vic - Property Name, Upper Hopkins Land Management Group, PanyyabyrLandcare Group and Glenthompson Landcare Group (Interaction 15) 17/3/22 Webinar - West Gippsland (virtual) - South Gippsland Landcare Network, Bass Coast Landcare Network (Interaction 18) 16/3/22 Workshop - Deniliquin-Tocumwal, NSW - Moroco West, Deniliquin-Kolety Lagoons Landcare Group (Interaction 22) 16/3/22 Workshop - Barham, NSW - Western Murray Land Improvement Group (Interaction 26) 3/3/22 Workshop - Buffalo, Vic - Buffalo Community Hall, Sout Gippsland Landcare Network, Bass Coast Landcare Network (Interaction 42) 2/3/22 Workshop - Balnarring/Red Hill, Vic - Mornington Peninsula Landcare Network, Melbourne Water and Port Philip and Westernport CMA (Interaction 50) 1/3/22 Workshop - Bunyip, Vic - Sherwood Park Orchard, Melbourne Water, Steels Creek Landcare, Cannibal Creek Landcare, Westernport Catchment Landcare Network / Sherwood Park Orchard, PPWCMA (Interaction 55) March 2022, Field day and workshop Portland Vic, Feb 2022, Zoom seminar Remarkable NRM, Atherton Tablelands Handout prepared for Blackwood Valley Small Landholders Group Summer School 28/2/22 - Steels Creek, Vic - workshop (interaction 30) 8/12/21 - Araluen, NSW with Bellaringa and Kikiamah research visits to trap O. vacca (attendees 4) 7/12/21 - Dung beetle monitoring - Araluen Valley (NSW)

		7/12/21 – Wilson Inlet Catchment Council planning meeting for the development of localized monitoring program (WA) 5/12/21 - Candelo, NSW with Far South Coast Landcare Association, South East LLS, property Maloola (attendees - 15) 1/12/21 - Bega Local Land services - Workshop - Candelo (NSW) 13/11/21 - Mornington Penisula Farmers Group - Webinar (Vic) (attendees - 20) 6/11/21 - Southern Farming Systems Dung Beetle Field Day - Inverleigh (Vic) (attendees 30) 5/11/21 - Hagley Farm School - Webinar (Tas) (attendees 24) 3/11/21 – Spring Field Day, Cressy (Tas) (attendees est. 30) Term 3 - Collaboration with Northcliffe District High School staff and students in locally significant applied science dung beetle unit (WA) The Plant Surveillance Network 2021 Annual Surveillance Workshop (~100 participants) (WA) Western Australian Landcare Facilitators (11 participants) (WA) Australian Entomological Society 2021 Conference (Organized Dung Beetle Symposium; ca 300 conference attendees) Numerous (27) livestock producers have participated in semi-structured interviews, and several (5) livestock producers have participated in a focus group. These interviews and focus group elucidate common perceptions of dung beetles as well as information on anthelmintic use and how this relates to the perception of dung beetles. A result of these interviews is that farmer awareness of dung beetles is increased by their participation in the interview. 29/10/21 - Kurz Dung Beetle Day – Donnybrook (WA) 28/10/21 - Corowa District Landcare & Holbrook Landcare Network - Webinar (NSW) (attendees 45) 29/9/21 - Grasslands Society of Southern Australia - Webinar (Vic/NSW/SA) (attendees 67) 12/8/21 - Hovell's Creek, NSW webinar given to the Hovell's Creek Landcare group (attendees - 18) 6/8/21 – Inspiring WA event Celebrating Dung Beetles in Northcliffe (WA) 30/7/21 - Wagga Wagga, NSW webinar given at the Livestock forum (attendees - 85) 28/7/21 - Culcairn, NSW Wilksch Estate - workshop with Holbrook Landcare network (attendees - 15) 28/5/21 - Denbarker Grazing Matcher Day (WA) 20/5/21 - workshop with Glenaroua Land Management group, SW Goulburn Landcare (attendees - 24) 10/5/21 - Mt Barker Community College – presentation to 4 Ag Science classes (WA) 19/4/21 In NZ on 19/4/21, MWLR responded to an urgent high-level request for information on dung beetles from Dr Gerald Rys, Principal

		Science Advisor, Science Policy and Trade Group, Ministry for Primary Industries (NZ Government): a) Is there a reduction in nutrient runoff to waterways? b) Is nitrogen leaching reduced? c) Is soil structure and water holding capacity improved? d) Is pasture productivity improved? e) Are fertiliser requirements reduced? f) How long does it take for beetles to become effective after being released on farm? 16/4/21 - Benalla, Vic workshop with Gecko Clan Landcare network (attendees - 28) 15/4/21 - Creighton's Creek (via Euroa), Vic workshop with Creighton's Creek Landcare group (attendees - 23) 4/4/21 - Talgarno, Vic workshop with Wise's Creek and Talgarno Landcare group (attendees - 26) 3/4/21 - Donnybrook Future Farming Forum – generic dung beetle presentation with specific information on species recovered within 100km (WA) 26/3/21 Noorinbee, Vic - Woodmancote Lowline Stud: property assessment / outreach / O. vacca nursery Attendees 4 18/3/21: Dr B Doube Phone seminar with Mt Remarkable NRM, Atherton, 10 attendees 11/3/21: Mount Barker Agricultural Bureau, Mt Barker, SA; 35 attendees 6/3/21: Rural Solutions SA, Department of Primary Industries and Regions, workshop and field visit, Woodrise Station, Limestone Coast; 20 attendees 5/3/21: The Grassland Society of Southern Australia – Limestone Coast Branch ‘Gearing Up for the Season’ field day (included workshop presentation). Ben Stark’s 753 Old Kingston Rd, Stewart Range; 40 attendees 4/3/21 Hamilton, Vic - Chrome Sheep Stud: property assessment / outreach Attendees 5 4/3/21 Hamilton, Vic - Summit Park Stud: property assessment / outreach Attendees 6 3/3/21 Portland, Vic - Cashmore Park, South West Prime Lamb Group: workshop / field day Attendees 22 3/3/21 Presentation at Mingenew Irwin Group Trial Review, 40 attendees. 2/3/21 Beeac, Vic - Mingawalla, Upper Barwon Landcare Network, SFS: workshop / field day Attendees 16 1/3/21: presentation to Naracoorte High School Ag students, Struan SA; 12 attendees 17/2/21 lesson to Year 10’s at Western Australian College of Agriculture Morawa 8/12/20 - dung beetle workshop at The Living Classroom Bingara NSW (Northern Slopes Landcare), 10 people (UNE)

		3/12/20 - Dung Beetle Webinar with Upper Barwon Landcare Network (COVID 19 restrictions) – hosted via Zoom (SFS) 3/12/20 Webinar Geelong region, Vic - Upper Barwon Landcare Network: Attendees 30 25/11/20 Yaven Creek, NSW - Riverina Highlands Landcare Group: Attendees 22 23/11/20 Big Springs, NSW - Kyeamba Landcare Group: Attendees 25 12/11/20 – WA Landcare Network online conference - http://www.landcarewa.org.au/resources/landcare-video-presentations/2020-wa-landcare-network-annual-general-meeting-and-network-gathering-12-november-2020/ 10/11/20 Cobargo, NSW - Barrabaroo Catchment Area Landcare Group: workshop / nursery setup Attendees 14 29/10/20 – Coolbinia Primary School – 8 presentations to approx. 200 students. Learnt about the benefits of dung beetles, were able to view live dung beetles and then watched the burial action of dung beetles in “ant farms” and fish tanks over the following weeks. 21/10/20 Somerton, NSW - Tamworth regional Landcare Association: workshop / field day Attendees 18 14/10/20 Finley High School NSW - Corowa District Landcare & Petaurus Education: workshop / seminar / nursery Attendees 34 13/10/20 Oaklands, NSW - Corowa District Landcare & Petaurus Education: workshop / seminar / nursery Attendees 68 8/10/20 Webinar Kilcunda region, Vic - Bass Coast Landcare Network: seminar Attendees 25 26/9/20 – Tamworth NSW (Tamworth Regional Landcare), 12 people (UNE) 21/9/20 – Somerton NSW (North West LLS Regional Agriculture Landcare Facilitators) ~8 people. This was the monitoring workshop that Russ presented at when delivering monitoring kits so it will probably appear in his list of events (UNE) 17/9/20, presentation to MacKillop Farm Management Group collaborators and Naracoorte High School students, Struan SA; 20 attendees 16/9/20 Webinar Toora region, Vic - Westernport Catchment Landcare Network: seminar Attendees 30 8/9/20 Lesson to Year 3- 6 at Dowerin District High School 1/9/20: Webinar Dubbo region, NSW - Central West Land Management Group: Attendees 30 Aug 2020 Mardella WA – farmer group awareness session, 25 people 30/7/20: Hands on lesson with year 11’s at Western Australian College of Agriculture Morawa 30/7/20 Webinar by Geocatch - https://www.facebook.com/watch/?v=766209164217293 3/7/20: Presentations at Western Australian College of Agriculture Morawa Field Day, 20 Attendees.

		5/6/20; Webinar for North Central CMA, Hunter Valley; approx. 40 attendees 20/5/20: Rolling Out Dung Beetles in New Zealand Authors: Simon Fowler, Manaaki Whenua Landcare Research; Andrew Barber, Agrilink NZ; Shaun Forgie, Dung Beetle Innovations Link to Webinar https://www.youtube.com/watch?v=y9ArIlEErCA Semi-structured interviews over Zoom or telephone have been conducted with 20 producers located throughout Australia. These interviews elucidate common perceptions of dung beetles, and broadly gauge the awareness amongst producers of the benefits of dung beetles. A result of these interviews is that farmer awareness of dung beetles is increased by their participation in the interview Temora NSW Community education workshops with Russ Barrow http://www.farmlink.com.au/project/dung-beetles Gippsland area VIC Project information presentations and discussions at farmer/community group meetings (and individuals) including Southern Farming Systems Board Committee, Southern Farming Systems Gippsland Branch, Southern Farming Systems Tasmania Branch, Southern Farming Systems Western Victoria branch, Gippsland Agricultural Group, East Gippsland Landcare Network, Far East Victoria Landcare and Maffra and District Landcare Network 19/8/19 South West WA Manjimup – presentation to Rotary 12/9/19 Kudardup Lower Blackwood LCDC – presentation to members 20/9/19 Walpole – presentation as part of Wonders of Walpole event 4/10/19 Perth – presentation at State NRM conference 19/11/19 **Harvey** – presentation to South West Catchments Council AGM gathering and Harvey Ag College students 21/11/19 **Manjimup** – presentation to Warren Catchments Council members – AGM and project wrap. 27-28/9/19 **Kyogle NSW** - Shared stall with Richmond Valley-Border Ranges Landcare group at the Kyogle show in September 2019. Brochures used were created by CSU. 19/3/19 **Mt Compass, SA** Producer Forum 28/3/2019 **UWA, WA** training workshop with collaborators 9/4/2019 **Portland Region, Vic**. Producer forum / meeting 20/6/2019 **Heywood Vic,** Training of staff and producers linked to SWPLG. 24/7/2019 **Warrah, NSW**. Seminar at AGM of Upper Mooki Landcare group. 31/7/2019 **Bairnsdale, Vic**. Training workshop for Southern Farming Systems staff. 7/9/19 **Mudgegonga**, **Vic**. Workshop with DBSI and producers to establish farmer nurseries and arenas. 8/9/2019 **Mitta Mitta, Vic.** Spoke at Landcare Vic event and workshop for producers. **CSU, Wagga, NSW**. (27/09/2019) Opening of Mass Rearing centre @CSU Presentation given at meeting associated with event. **CSU, Wagga, NSW**. (3/10/2019) Chemical Ecology Workshop.

		Orange, NSW (4/11/2019). Central Tablelands Local Land Services presentation to producers and volunteers. **Molong, NSW (**5/11/2019) Training workshop with Central Tablelands Landcare. **Sydney, NSW**. (14/11/2019) Mass Rearing/Distribution workshop with collaborators. **Hamilton, NZ**. (20/11/2019) Meeting with Manaaki Whenua – Landcare Research staff. **Otorohanga, NZ** (21/11/2019) Visit to field site, field walk and training. **Whenuapai, NZ.** (22/11/2019) Visit to Dung Beetle Solutions to observe mass rearing facility. **Shelley Beach, NZ**.(22/11/2019) Farm visit with producer. Field walk. **Swifts Creek, Vic.** (3/12/2019) Producer forum/workshop **Meerlieu, Vic**.(4/12/2019) Producer forum /workshop **Noorinbee North, Vic**.(5/12/2019) Producer forum and workshop. **Kambah, ACT**. (12/12/2019**)** Producer visit and field assessment of dung beetle activity. MIG meeting, **Mingenew** Shire of Murray - Presentations & conversations with interested parties about dung beetle monitoring **Peel-Harvey** Catchment Council - Presentations & conversations with interested parties about dung beetle monitoring **Middle Swan** Primary School - Presentations & conversations about dung beetle monitoring & education possibilities. **Margaret River** Senior High School - Presentations & conversations dung beetle monitoring & education possibilities.
Social media presence	Dung Beetle Ecosystem Engineer Facebook page - 124 post Warren Catchment Council (dungbSW) – 386 posts (reach 2500+) Southern Farming Systems Group Page – 53 posts Gippsland Agricultural Group Page - 19 posts Mingenew Irwin Group –	Posts to Dung Beetle Ecosystem Engineers page: 1. 26/1/23 - update regarding Graeme Stevensons OAM award fro work on dung beetles in Tasmania (Interaction 792) 2. 26/1/23 - informing followers of recent publication on lysimeter studies (Interaction 1057) 3. 19/1/23 - post informing growers about chicory tand its anti-parasitic activity on some GI nematodes (Interaction 3329) 4. 5/1/23 - information regarding the results of our monitoring studies on the flood impacted regions around Deniliquin (Interaction 1528) 5. 3/1/23 - post Smart Farms workshop at Aruna Estate with Southern Highlands Landcare Network and RegenAction Wingecarribee (Interaction 1529) 6. 11/12/22 - reporting ABC article talking about Bubas bison in SA (Interaction 781) 7. 4/12/22 - post on Smart Farms field day at Mt Gambier, OB Flat, Woolumbool and Wrattonbully with Landscape South Australia Limestone Coast (Interaction 1990) 8. 2/11/22 - repost of Smart Farms workshop in Berry. Original post from the Grow Love project (metrics not available on re-post) (Interaction 0) 9. 1/11/22 - time lapse video of Onthophagus taurus on a dung mass (Interaction 7329) 10. 27/9/22 - Henty Field Days - 15 species locally and 30 species on pin board (Interaction 1133)

	18 FB posts, 12 Twitter posts	11. 12/9/22 - Henty field days - Riverina and Murray NRM (Interaction 746) 12. 7/7/22 - highilights a news article from Bernard Doube - Onitis vanderkelleni (Interaction 464) 13. 17/9/22 - featuring work out of CSIRO - Gymnopleurus sturmi (Interaction 620) 14. 13/6/22 - Onitis viridulus ID sheet (Interaction 731) 15. 3/6/22 - update of redistribution efforts for Bubas bison (Interaction 2719) 16. 15/5/22 - Onthophagus nigriventris ID sheet (Interaction 662) 17. 13/5/22 - highlights story out of CSU appearing in the Daily Advertiser - Wagga (Interaction 711) 18. 11/5/22 - highlights work out of CSIRO appearing in the Canberra Times (Interaction 795) 19. 6/5/22 - Agriculture Victoria, South West Prime Lamb Group - Onthophagus mniszechi (Interaction 736) 20. 4/5/22 - highlights a story in The National Tribune on Gymnopleurus sturmi (Interaction 2332) 21. 4/5/22 - southern NSW - A. fimetarius (Interaction 580) 22. 14/4/22 - Upper Hopkins Land Management Groupa and Panyyabyr Landcare Group / Kalanoa - A. fimetarius, O. aygulus, O. taurus, O. australis and O. mniszechi (Interaction 945) 23. 6/4/22 - Liatongus militaris ID sheet (Interaction 760) 24. 5/4/22 - Deniliquin-Kolety Lagoons Landcare Group / Moroco West - various species (Interaction 783) 25. 26/3/22 - Western Murray Land Improvement Group - D. gazella, O. taurus, E. intermedius (Interaction 544) 26. 26/3/22 - Western Murray Land Improvement group workshop - O. taurus, E. fulvus, G. spiniger, O. vacca (Interaction 550) 27. 10/3/22 - Weddin Landcare Network (Interaction 511) 28. 5/3/22 - Mornington Peninsula Landcare Network, Dunns Creek Landcare , Melbourne Water / Kingston Park Stud - Bubas bubalus (Interaction 843) 29. 1/3/22 - Melbourne Water, Steels Creek Landcare, Cannibal Creek Landcare, Westernport Catchment Landcare Network / Sherwood Park Orchard, PPWCMA - various species (Interaction 888) 30. 18/2/22 - Central west LLS, Weddin Landcare / Caragabal West - various species (Interaction 1554) 31. 16/2/22 - Central West LLS / Willydah (Interaction 927) 32. 15/2/22 - Central West LLS / Emu Logic - D. gazella, E. intermedius, O. alexis, Hister nomas (Interaction 931) 33. 15/2/22 - Onthophagus tamworthi (Interaction 1691) 34. 15/2/22 - Liatongus militaris (Interaction 476) 35. 27/1/22 - Onthophagus capella ID sheet (Interaction 508) 36. 1/12/2021 - Far South Coast Landcare Association, South East LLS, property Maloola, A. fimetarius, E. fulvus, O. pecuarius, O. binodis, O. granulatus, O. taurus, H. nomas Interaction # 1930 37. 14/11/21 - Mornington Penisula Farmer Discussion group, Interaction # 1284 38. 6/11/21 - Copris hispanus ID sheet Interaction # 1075

		39. 6/11/21 - Southern Farming System, Corangamaite CMA, Dung Beetle Field Day, O. vacca, E. fulvus, A. fimetarius, O. australis, O. binodis, O. taurus, Omorgus sp. Interaction # 1075 40. 1/11/21 - CSIRO, Black Mountain, Canberra, news post based on Valerie Caron interview Interaction # 253 41. 30/10/21 - Onthophagus dandalu ID sheet Interaction # 497 42. 11/10/21 - news post encouraging Facebook followers to complete a survey on biological control, section on dung beetles in the survey Interaction # 813 43. 7/10/21 - E. intermedius ID sheet Interaction # 312 44. 7/10/21 - Did you know? #10 - How much dung do cattle and sheep produce Interaction # 996 45. 29/9/21 - Wymah monitoring cicruit - via Wagga, O. taurus, E. fulvus, B. bison, A. lividus Interaction # 926 46. 10/9/21 - A. fimetarius ID sheet Interaction # 1959 47. 8/9/21 - link to a popular science article suggesting CO2 is bad for insects too Interaction # 475 48. 23/8/21 - E. fulvus ID sheet Interaction # 1034 49. 1/8/21 - Did you know? #8 - Dung beetles sp often have mites on them Interaction # 2294 50. 287/21 - Did you know? #9 - Dung beetles start their lives inside a ball of dung Interaction # 1982 51. 2/7/21 - Onitis caffer populations discovery story Interaction # 3708 52. 22/6/21 - E. africanus video - can you ID the beetle Interaction # 385 53. 19/6/21 - E. pallipes ID sheet Interaction # 1249 54. 6/6/21 - E. africanus ID sheet Interaction # 1348 55. 2/6/21 - A. fimetarius video and story Interaction # 775 56. 28/5/21 - link io ABC story on B. bison Interaction # 401 57. 24/5/21 - Glenaroua Land Management group, SW Goulburn Landcare, B. bison, A. fimetarius, A. lividus Interaction # 446 58. 17/5/21 - near Henty, NSW, video on field trapping of B. bison Interaction # 1915 59. 7/5/21 - O. binodis ID sheet Interaction # 1867 60. 30/4/21 - multiple properties visited, including Hazeldean, A. fimetarius story Interaction # 605 61. 18/4/21 - B. bison trapping story Interaction # 2170 62. 17/4/21 - Gecko Clan Landcare, Interaction # 782 63. 10/4/21 - B. bison Interaction # 806 64. 26/3/21 - Far East Victoria Landcare, O. taurus, E. fulvus, O. binodis, O. australis, O. vacca Interaction # 1240 65. 25/3/21 - SFS. Topsoils Project and East Gippsland Landcare Network, O. taurus, E. fulvus, O. binodis, O. australis, O. vacca Interaction # 597 66. 24/3/21 - South Gippsland Landcare Network, O. taurus, E. fulvus, G. spiniger Interaction # 224 67. 23/3/21 - Westernport Catchment Landcare Network, A. fimetarius, O. taurus, E. fulvus, O. binodis Interaction # 333

		68. 22/3/21 - Blairgowrie, Holbrook Landcare Network, E. fulvus, E. africanus, B. bison Interaction # 575 69. 22/3/21 - Macedon Ranges Shire Council, Port Phillip and Westernport CMA, A. fimetarius, O. taurus Interaction # 575 70. 21/3/21 - Mingawalla, Upper Barwon Landcare Network, SFS, A. fimetarius, B. bison, E. fulvus, O. aygulus and O. taurus Interaction # 689 71. 21/3/21 - South West Prime Lamb Group, O. taurus, E. fulvus, O. mniszechi, O. posticus Interaction # 301 72. 5/3/21 - Cashmore Park, Summit Park, Chrome Sheep Studs, O. taurus and E. fulvus Interaction # 1207 73. 1/3/21 - Southern Farming Systems, none Interaction # 2835 74. 15/2/21 - none Interaction # 513 75. 25/1/21 - Did you know #7/dung rollers - S. rubrus and spinipes Interaction # 1074 76. Facebook Tarcutta, NSW - Tarcutta House: Bubas bison Interaction with 682 77. Facebook Bemboka, NSW: Hister nomas Interaction with 837 78. Facebook Bemboka, NSW: Hister nomas Interaction with 341 79. Facebook Wymah, NSW - Rennylea: Interaction with 283 80. Facebook: beetle identification sheet / Bubas bison Interaction with 2285 81. Facebook: beetle identification sheet / Onthophagus australis Interaction with 1414 82. Facebook: beetle identification sheet/ Onthophagus vacca Interaction with 608 83. Facebook: beetle identification sheet / Onitis aygulus Interaction with 1079 84. Facebook Nangus, NSW - Kimo Estate: monitoring / Bubas bison Interaction with 743 85. Facebook: beetle identification sheet / Onitis alexis Interaction with 397 86. Facebook: https://www.mla.com.au/.../the-life-of-a-dung-beetle.../ Interaction with 147 87. Facebook Araluen, NSW - Kikiamah: monitoring / Onitis caffer Interaction with 404 88. Facebook: beetle identification sheet / Onitis caffer Interaction with 285 89. Facebook Temora, NSW - Farmlink: farmer nursery / Onthophagus vacca Interaction with 568 90. Facebook: Did you know #1 / Bubas bubalus Interaction with 1175 91. Facebook: highlight children's dung beetle book online resource Interaction with 983 92. Facebook: beetle identification sheet / Onitis pecuarius Interaction with 563 93. Facebook Culcairn, NSW - Wyuna: none Interaction with 665 94. Facebook: Did you know #2/ Bubas bison Interaction with 1318 95. Facebook: beetle identification sheet / Onthophagus mniszechi Interaction with 353

		96. Facebook Tumbarumba, NSW - Dalkeith: farmer nursery / Onthophagus vacca Interaction with 262 97. Facebook: Did you know #3/ Scarabaeus sacer Interaction with 1164 98. Facebook: beetle identification sheet /Aphodius fimetarius Interaction with 1039 99. Facebook: Did you know #4/ Aphodius fimetarius, Geotrupes spiniger, Aulocopris matthewsi Interaction with 483 100. Facebook: beetle identification sheet / Onthophagus taurus Interaction with 1051 101. Facebook Corowa region, NSW - Corowa District Landcare & Petaurus Education: Onthophagus vacca Interaction with 1024 102. Facebook Somerton, NSW - Tamworth regional Landcare Association: none Interaction with 786 103. Facebook: beetle identification sheet / Geotrupes spiniger Interaction with 536 104. Facebook Cobargo, NSW - Barrabaroo CALG / Brandywine: O. binodis, O. granulatus, A. fimetarius Interaction with 498 105. Facebook: Did you know #5/ native beetles including O. mniszechi and O dandalu Interaction with 1619 106. Facebook Big Sorings, Yaven Creek, NSW - Kyeamba & Riverina Highlands Landcare Group: A. fimetarius, E. fulvus, pallipes, africanus, intermedius, O. taurus, O. alexis, O. aygulus Interaction with 762 107. Facebook: beetle identification sheet / Onthophagus granulatus Interaction with 429 108. Facebook Candelo, NSW - Onthophagus binodis Interaction with 1730 109. Facebook Wymah, NSW - Rennylea: beetle activity/ Onthophagus taurus and Euoniticellus fulvus Interaction with 1487 110. Facebook: Did you know #6/scarabs in general - O. alexis Interaction with 499 111. Facebook: beetle identification sheet / Onthophagus posticus Interaction with 1730 112. Facebook: beetle identification sheet / Digitonthophagus gazella Interaction with 1194 113. Facebook: Did you know #7/dung rollers - S. rubrus and spinipes Interaction with 1074 114. Facebook Bega, NSW: Interaction with 513 115. Facebook Inverleigh, Vic - Southern Farming Systems: Interaction with 2835 116. Facebook - Cashmore Park, Summit Park, Chrome Sheep Studs: O. taurus and E. fulvus Interaction with 1207 117. Facebook south western Vic - Mingawalla, Upper Barwon Landcare Network, SFS: A. fimetarius, B. bison, E. fulvus, O. aygulus and O. taurus Interaction with 689 118. Facebook Tyrendarra, Vic - South West Prime Lamb Group: O. taurus, E. fulvus, O. mniszechi, O. posticus Interaction with 301 119. Facebook - Blairgowrie, Holbrook Landcare Network: E. fulvus, E. africanus, B. bison Interaction with 575

		120. Facebook Chintin, Vic - Macedon Ranges Shire Council, Port Phillip and Westernport CMA: A. fimetarius, O. taurus Interaction with 575 121. Facebook Labertouche, Vic - Westernport Catchment Landcare Network: A. fimetarius, O. taurus, E. fulvus, O. binodis Interaction with 333 122. Facebook Toora, Vic - South Gippsland Landcare Network: O. taurus, E. fulvus, G. spiniger Interaction with 224 123. Facebook Bengworden, Vic - SFS. Topsoils Project and East Gippsland Landcare Network: O. taurus, E. fulvus, O. binodis, O. australis, O. vacca Interaction with 597 124. Facebook Wairewa, Vic - Far East Victoria Landcare: O. taurus, E. fulvus, O. binodis, O. australis, O. vacca Interaction with 1240 Other groups: 1. 6/5/22 - Agriculture Victoria, South West Prime Lamb Group - Onthophagus mniszechi (interaction 627) 2. 5/5/22 - - Aphodius fimetarius (interaction 507) 3. 14/4/22 - Upper Hopkins Land Management Groupa and Panyyabyr Landcare Group / Kalanoa - A. fimetarius, O. aygulus, O. taurus, O. australis and O. mniszechi (interaction 872) 4. 6/4/22 - Liatongus militaris ID sheet - Liatongus militaris (interaction 692) 5. 5/4/22 - Deniliquin-Kolety Lagoons Landcare Group / Moroco West - Aphodius fimetarius, Digitonthophagus gazella, Euoniticellus africanus, Euoniticellus fulvus, Euoniticellus intermedius, Onitis alexis, Onitis aygulus and Onthophagus taurus (interaction 716) 6. 26/3/22 - Western Murray Land Improvement Group - D. gazella, O. taurus, E. intermedius (interaction 521) 7. 10/3/22 - South Gippsland Landcare Network, Bass Coast Landcare Network/ Buckley Park Community Farm - O. taurus, E. fulvus, G. spiniger, O. vacca (interaction 511) 8. 5/3/22 - Weddin Landcare Network - (interaction 511) 9. 1/3/22 - Mornington Peninsula Landcare Network, Dunns Creek Landcare , Melbourne Water / Kingston Park Stud - Bubas bubalus (interaction 823) 10. 18/2/22 - Melbourne Water, Steels Creek Landcare, Cannibal Creek Landcare, Westernport Catchment Landcare Network / Sherwood Park Orchard - Onthophagus taurus, Onthophagus binodis, Onthophagus australis, Euoniticellus fulvus, Aphodius lividus, Geotrupes spiniger. (interaction 847) 11. 16/2/22 - Central west LLS, Weddin Landcare / Caragabal West - Hister nomas, Digitonthophagus gazella, Euoniticellus africanus, Euoniticellus fulvus, Euoniticellus intermedius, Eoniticellus pallipes (interaction 1497) 12. 15/2/22 - Central West LLS / Willydah - Digitonthophagus gazella, Aphodius lividus, Onitis alexis, Euoniticellus intermedius, Onthophagus taurus (interaction 907)

		13. 15/2/22 - Central West LLS / Emu Logic - Digitonthophagus gazella, Euoniticellus intermedius, Onitis alexis, Hister nomas (interaction 931) 14. 15/2/22 - Onthophagus tamworthi (interaction 1691) 15. 15/2/22 - Liatongus militaris (interaction 476) 16. 27/1/22 - Onthophagus capella (interaction 494) 17. Dec 2019 https://youtu.be/1hd-dz0CwaE Mass releases of 2 spp of dung beetles on the Mahia Peninsula, NZ in Dec 2019. Video Clip put together by Hawke's Bay Regional Council
Peer-reviewed scientific papers / books	8	Zamprogna, A., Hajji, H. and Janati-Idrissi, 2022. Sexual dimorphism in *Gymnopleurus sturmi* (Macleay, 1821) (Coleoptera: Scarabaeidae), a palearctic dung beetle being imported to Australia, Australian Entomologist. 49 (1)-12-22. Noriega, Jorge Ari; Halliday, Bruce; Weston, Paul; Thotagamuwa, Agasthya; Gurr, Geoff). Beyond phoresy: symbioses between dung beetles (Coleoptera: Scarabaeidae: Scarabaeinae) and mites (Acari). Entomologia Generalis (2022). DOI: 10.1127/entomologia/2021/1406 Manuscript titled "A baited time sorting pitfall trap allowing more temporal fidelity of dung beetle activity." was submitted to The Coleopterists Bulletin and has been accepted and is currently with the journal editor. Doube, B, Thotagamuwa, A & Doube, L 2021, Dung burial by beetles, in Recarbonizing global soils: a technical manual of recommended management practices, Volume 3: Cropland, Grassland, Integrated systems and farming approaches - Practices overview, Geneva, Food and Agriculture Organization. Doube, B, Thotagamuwa, A & Doube, L 2021, Selection and introduction of dung beetles to beetle-depauperate regions in southern Australia to increase soil organic carbon levels, in Recarbonizing global soils: a technical manual of recommended management practices, Volume 4: cropland, grassland, integrated systems and farming approaches – Case-studies, Geneva, Food and Agriculture Organization. Aislabie J, McLeod M, McGill A, Rhodes P, Forgie S 2020. Impact of dung beetle activity on the quality of water percolating through Allophanic soil. Soil Research 59, 266-275. https://www.publish.csiro.au/sr/sr19182 Rapalai BL 2020, Evidence of restricted gene flow and local adaptation in a translocated dung beetle. Thesis for Journal of Evolutionary Biology Doube, BM, Thotagamuwa, A & Doube, L 2020, Dung burial by beetles and its effect on soil organic carbon, SEGments 36 (2), pp 10–15. SEGments is the journal of the Scientific Expedition Group Inc.
Scientific conference presentations	12	Talkin Soil Health on 11 August 2022 in York. Web address: https://www.soilhealth.com.au/ Dung derived pasture types and the influence on temperate dung beetle species, Thomas Heddle presented PhD work at Australian Entomological Society Conference 9/12/21 Using the MyPestGuideTM mobile phone app to monitor the activity of exotic dung beetles, J Berson, presented to The Plant Surveillance Network 2021 Annual Surveillance Workshop.

		Deducing the historical economic impacts of exotic dung beetles (Coleoptera: Scarabaeinae) on the livestock industry in Western Australia, M Vieira, presented to the 2021 Australian Entomological Society Conference 9/12/21. Density and Evenness increase ecosystem multifunctionality of dung beetle assemblages, D Anderson, presented to the 2021 Australian Entomological Society Conference 9/12/21. Targeted-selective-treatment of gastrointestinal nematodes and the effects on dung beetles, M Lewis, presented to the 2021 Australian Entomological Society Conference 9/12/21. Olfactory responses of introduced dung beetles, Bubas bison and Onthophagus vacca to dung volatile cues, Nisansala PERERA PhD work presented to the 2021 Australian Entomological Society Conference 9/12/21 Quantifying the Effects of Introduced Dung Beetles on Ecosystem Multifunctionality in Pasture Ecosystems, Fevziye HASAN presented to the 2021 Australian Entomological Society Conference 9/12/21 Impact of dung beetle activity on infective stages of gastrointestinal nematodes in dung: A modelling approach, Paul WESTON presented to the 2021 Australian Entomological Society Conference 9/12/21 Challenges associated with rearing Gymnopleurus sturmi (Coleoptera: Scarabaeidae), a new dung beetle species for Australia, Alberto ZAMPROGNA presented to the 2021 Australian Entomological Society Conference 9/12/21 Inoculating eggs with gut microbiome improves dung beetle fitness in a newly imported species, Valerie CARON presented to the 2021 Australian Entomological Society Conference 9/12/21 1-4/12/19 2019 Entomology Conference Brisbane (Bernard Doube) 3/10/2019 RACI Chemical Ecology Symposium (Russ Barrow)

8.2 Dung beetle releases

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
1	WA	Denmark	cattle	*O. vacca*	50	Field cage	September 2017	n/a
2	WA	Denmark	cattle	*O. vacca*	50	Field cage	September 2017	n/a
3	NSW	Port Macquarie	cattle	*O. vacca*	20	Field cage	September 2017	n/a
4	WA	Manjimup	cattle	*O. vacca*	1250	to the field	August 2018	n/a
5	Vic	Keiwa Valley	cattle	*O. vacca*	50	field tent	spring 2018	n/a
6	Vic	Keiwa Valley	cattle	*O. vacca*	50	field tent	spring 2018	n/a
7	Vic	Keiwa Valley	cattle	*O. vacca*	50	field tent	spring 2018	n/a
8	Vic	Keiwa Valley	cattle	*O. vacca*	50	field tent	spring 2018	n/a
9	WA	Manjimup	cattle	*O. vacca*	approx 2500	placed in protected cages in nursery	spring 2018	none available
10	NSW	Armidale	cattle	*O. vacca*	approx 2500	placed in hoop house (large field cage)	spring 2018	Live third instars present in December 2018
Component 2 Spring 2019: French O. vacca nurseries Protocol 1								
Spring 2019: French O. vacca nurseries								
11	WA	Geraldton, MIG	cattle	*O. vacca*	170	field nursery		
12	WA	Geraldton, MIG	cattle	*O. vacca*	170	field nursery		

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
13	WA	North Dandalup	cattle	*O. vacca*	170	field nursery		
14	WA	Lake Clifton	cattle	*O. vacca*	170	field nursery		
15	WA	Nannup, Vasse Hwy, Cundinup WA 6275	sheep	*O. vacca*	220	field nursery		
16	WA	Wilga	cattle	*O. vacca*	170	field nursery		
17	WA	Manjimup	cattle	*O. vacca*	170	field nursery	spring 2019	
18	WA	Rosa Brook	cattle	*O. vacca*	170	field nursery	spring 2019	
19	WA	Harvey	cattle	*O. vacca*	170	field nursery	spring 2019	
20	WA	Yanmah	cattle	*O. vacca*	170	field nursery	spring 2019	
21	SA	Kangaroo Island South Coast Rd MacGillivray SA 5223	cattle	*O. vacca*	170	field nursery		
22	SA	Wootoona, Karra Yerta Rd, Flaxman Valley SA 5235	cattle	*O. vacca*	170	field nursery		
23	SA	Wrattonbully Rd, Wrattonbully, 5271	cattle, loam	*O. vacca*	170	field nursery		
24	SA	Wrattonbully Rd, Wrattonbully, 5271	cattle, sand	*O. vacca*	170	field nursery		
25	Vic	Cashmore Park, Wilmot's Road, Cashmore VIC 3305	sheep	*O. vacca*	170	field nursery	4/09/2019	20-Nov
26	Vic	Mayberry Rd, Tyrendarra Vic 3285	cattle	*O. vacca*	170	field nursery	5/09/2019	
27	Vic	Mitta Mitta	horse	*O. vacca*	approx 100			

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
28	Vic	Mitta Mitta	horse	*O. vacca*	approx 100			
29	Vic	Mitta Mitta	cattle	*O. vacca*	approx 100			
30	Vic	Mitta Mitta	cattle	*O. vacca*	approx 100			
31	Vic	Mitta Mitta	cattle	*O. vacca*	approx 100			
32	Vic	Mudgegonga	horse	*O. vacca*	170	field nursery		
33	Vic	Mudgegonga	cattle	*O. vacca*	170	field nursery		
34	Vic	Mudgegonga	cattle	*O. vacca*	100	field nursery	?	
35	Vic	West Gippsland, Loch	cattle	*O. vacca*	170	field nursery	5-Sep-19	
36	Vic	218 Kolong Rd, Timboon Vic 3268	cattle	*O. vacca*	170	field nursery	5-Sep-19	
37	Vic	Yarra Valley, Kirkpatrick's Rd, Macclesfield VIC 3782	horse	*O. vacca*	170	field nursery		
38	Vic	Yarra Valley, Kirkpatrick's Rd, Macclesfield VIC 3782	cattle	*O. vacca*	170	field nursery		
39	NSW	Molong nr Orange	cattle	*O. vacca*	170	field nursery	11/09/2019	25-Nov-19
40	NSW	Old Bonalbo	cattle	*O. vacca*	170	field nursery	13/09/2019	4-Nov-19
41	Tas	Burnie	cattle	*O. vacca*	170	field nursery	12-Sep-19	28-Nov-19
42	Tas	Hobart	cattle	*O. vacca*	170	field nursery	12-Sep-19	
43	NSW	Quaama		*O. vacca*	200	field nursery	spring 2019	
44	NSW	Cobargo		*O. vacca*	200	field nursery	spring 2019	
45	NSW	Winslade		*O. vacca*	184	field nursery	spring 2019	
46	NSW	Cook		*O. vacca*	172	field nursery	spring 2019	
Component 3 Protocol - Spring 2019: French B. bubalus nurseries								

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
47	SA	Kangaroo Island South Coast Rd MacGillivray SA 5223	cattle	*B. bubalus*	12	field nursery		
48	SA	Wootoona, Karra Yerta Rd, Flaxman Valley SA 5235	cattle	*B. bubalus*	12	field nursery		
49	SA	1185 Wrattonbully Rd, Wrattonbully, 5271	cattle	*B. bubalus*	15	field nursery		
50	SA	Port Elliot	cattle	*B. bubalus*	12	field nursery		
51	SA	Port Elliot	cattle	*B. bubalus*	50	field nursery		
51	NSW	Farm nursery at CSU, Wagga Wagga	cattle	*B. bubalus*	10	field nursery	2019	
52	NSW	Farm nursery at CSU, Wagga Wagga	cattle	*B. bubalus*	40	field nursery	sept 2020	
Component 3 - Late spring 2019: Protocol 3 ex CSIRO vernalisation. Moroccan breeding O. vacca arenas								
53	NSW	Wagga	cattle	*O.vacca*	330	Arena		
54	NSW	Wagga	cattle	*O.vacca*	330	Arena		
55	SA	Port Elliot	cattle	*O.vacca*	330	Cage	13-Nov-19	
Component 4, early summer 2019: Protocol 3 - A second cohort of Moroccan *O. vacca Via CSIRO post vernalisation*								
56	Vic	near Portland Vic	cattle	*O.vacca*	approx 200		early summer	
57	Vic	near Portland Vic	cattle	*O.vacca*	approx 200		early summer	
58	Vic	near Portland Vic	cattle	*O.vacca*	approx 200		early summer	
Component 5, early summer 2019: Protocol 3 - A third cohort of Moroccan O. vacca via CSU								
59	WA	Harvey Ag College - Wokalup	cattle	*O.vacca*	500 total			
60	WA	Farmer 1	cattle	*O.vacca*				
61	WA	Farmer 2	cattle	*O.vacca*				

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
62	WA	Farmer 3	cattle	*O.vacca*				
63	WA	Farmer 4	cattle	*O.vacca*				
64	WA	Farmer 5	cattle	*O.vacca*				
Component 6 Early summer 2019 F1O. vacca from Creation Care n=15,000								
65	NSW				1000			
66	NSW				1000			
67	WA				2000			
68	WA				2000			
69	WA				1000			
70	Tas				1000			
71	SA	Bordertown			1500			
72	Vic	Portland			1500			
73	Vic	Portland			1500			
74	Vic	Portland			1500			
Component 7, some From UNE								
75	NSW	Callaghan's Creek	cattle?	*O.vacca French*	200	Field nursery	12/02/2020	
76	NSW	Callaghan's Creek	cattle?	*O.vacca French*	200	Field nursery	12/02/2020	
77	VIC	Myrtleford	cattle	O vacca	210	Field nursery	12/02/2020	
78	NSW	RMB916, near Mangoplah	cattle	O vacca	40	Field nursery	18/03/2020	
79	VIC	Noorinbee north	cattle?	O vacca	210	Field nursery	3/03/2020	
80	VIC	Oxley	cattle	O vacca	210	Field nursery	12/02/2020	
81	NSW	Big Springs	cattle	O vacca	210	Field nursery	12/02/2020	
82	NSW	Temora	cattle	O vacca	83	Field nursery	5/08/2020	
83	NSW	Mannus	cattle	O vacca	58	Field nursery	2/09/2020	
84	NSW	CSU farm Wagga	cattle	O. vacca	110	Field nursery A	Sep-20	
85	NSW	CSU farm Wagga	cattle	O. vacca	110	Field nursery B	Sep-20	
86	NSW	CSU farm Wagga	cattle	O. vacca	110	Field nursery C	Sep-20	

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
87		CSU farm Wagga	cattle	O. vacca	110	Field nursery D	Sep-20	
88	NSW	Holbrook	cattle	O. vacca, hybrid CSU	80	Field nursery	Oct-20	
89	NSW	Holbrook	cattle	O. vacca, hybrid CSU	80	Field nursery	Oct-20	
90	NSW	Oaklands Central School	sheep	O. vacca	100	Field nursery	13/10/2020	
91	NSW	Finley High School	Sheep and/or cattle	O. vacca	100	Field nursery	13/10/2020	
92	NSW	Savernake	sheep	O. vacca	130	Field nursery	13/10/2020	
93	NSW	Rennie	?	O. vacca	70	Field nursery	13/10/2020	
94	NSW	Daysdale	cattle	O. vacca	70	Field nursery	14/10/2020	
95	NSW	Cobargo	cattle	O. vacca	100	Field nursery	9/11/2020	
96	SA	Hillcrest Pastoral Co, 174 Minnie Crowe Road, Avenue Range SA 5273		O vacca pop 4, Moroccan	100	Field nursery	15-Nov-20	
97	Vic	131 Robertsons Rd, Bolwarra Vic 3305			200	Field nursery	15-Nov-20	
98	Vic	131 Robertsons Rd, Bolwarra Vic 3305			200	Field nursery	15-Nov-20	
99	WA	Warren Catchments Council			approx 240	Field nursery	15-Nov-20	
100	NSW			French O vacca	412		23-Nov-20	
101	NSW			French O vacca	488		7-Dec-20	
Component 8 - from CSU Wagga								
102	Tas	Launceston Primary school		O. vacca	100		15-Nov-20	
103	Tas	Hobart		O. vacca	100		15-Nov-20	
Component 9 - from CSIRO, 633: various types								
73	Tas	Burnie		Moroccan O vacca	418		10-Nov-20	
74	Vic	131 Robertsons Rd, Bolwarra Vic 3305		Moroccan O vacca	207		10-Nov-20	

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
Component 10 - Bubas bubalus from Creation Care To Mitta Mitta (11 nurseries)								
75	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
76	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
77	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
78	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
79	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
80	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
81	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
82	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
83	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
84	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
85	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
86	Vic	Mitta Mitta		*B. bubalus*	50		spring 2021	
Component 11 - Onitis caffer (most from Kingaroy 13 nurseries)								
87	NSW	Wauchope		Onitis caffer	approx 25		autumn 2020	
88	NSW	Wauchope		Onitis caffer	approx 25		autumn 2020	
89	NSW	Wauchope		Onitis caffer	approx 25		autumn 2020	
90	NSW	Old Bonalbo		Onitis caffer	approx 25		autumn 2020	
91	NSW	Old Bonalbo		Onitis caffer	approx 25		autumn 2020	
92	NSW	Old Bonalbo		Onitis caffer	approx 25		autumn 2021	
93	NSW	Old Bonalbo		Onitis caffer	approx 25		autumn 2021	
94	NSW	Old Bonalbo		Onitis caffer	approx 25		autumn 2021	
95	NSW	Old Bonalbo		Onitis caffer	approx 25		autumn 2021	
96	NSW	Old Bonalbo		Onitis caffer	approx 25		autumn 2021	
97	NSW	Old Bonalbo		Onitis caffer	approx 25		autumn 2021	
98	NSW	Old Bonalbo		Onitis caffer	approx 25		autumn 2021	
99	NSW	Armidale		Onitis caffer	approx 25		autumn 2021	

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
100	NSW	Tynong North		Onitis caffer	40	field cage	May-22	
101	WA	south west		Onitis caffer	60	field cage	May-22	
Component 12 - Orange district B bison winter 2021								
102	NSW	Orange	cattle	*B bison*	approx 50	field cage and field cores	winter 2021	
103	NSW	Bathurst	cattle	*B bison*	approx 50	field cage and field cores	winter 2021	
Component 13 - Bubas bison to Cowra (10 field nurseriers)								
104	NSW			*B bison*	50			
105	NSW			*B bison*	50			
106	NSW			*B bison*	50			
107	NSW			*B bison*	50			
108	NSW			*B bison*	50			
109	NSW			*B bison*	50			
110	NSW			*B bison*	50			
111	NSW			*B bison*	50			
112	NSW			*B bison*	50			
113	NSW			*B bison*	50			
Component 14 - B bison from CSU in 2020 (10 nurseries)								
114				*B bison*				
115				*B bison*				
116				*B bison*				
117				*B bison*				
118				*B bison*				
119				*B bison*				
120				*B bison*				
121				*B bison*				

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
122				*B bison*				
123				*B bison*				
Component 15 - Bubas bison from CSU 2021								
124	NSW	Cowra		*B bison*	40	Field nursery	Jun-21	
125	NSW	Belecky		*B bison*	40	1 nursery + soil core 10 beetles	Jun-21	
126		Mandurama		*B bison*	40	1 nursery	Jun-21	
127	NSW	Whoota		*B bison*	200	(2 x 100) in 2 field nurseries	Jun-21	
128	NSW	Gooloogong		*B bison*	10	field core	Jun-21	
129	NSW	Nyrang Creek		*B bison*	80	2 nurseries	Jun-21	
130	NSW	Darbys Falls		*B bison*	40	Field nursery	Jun-21	
131	NSW	Mandurama		*B bison*	50	1 nursery + soil core 10 beetles	Jun-21	
132	NSW	Eugowra		*B bison*	80	2 field nurseries	Jun-21	
133	NSW	Darbys Falls		*B bison*	80	2 field nurseries	Jun-21	
134	NSW	Darbys Falls		*B bison*	40	40 beetles 1 nursery + soil core 10 beetles	Jun-21	
135	NSW	Woodstock		*B bison*	40	40 beetles 1 nursery + soil core 10 beetles	Jun-21	

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
136	NSW	Wyangala		*B bison*	80	2 field nurseries	Jun-21	
137	NSW	Mandurama		*B bison*	80	2 field nurseries	Jun-21	
Component 16 - Bubas bison from CSU 2022								
138	VIC	Tynong North		*B bison*	100	Field nursery	May-22	
139	VIC	Steels Creek		*B bison*	200	2 Field nurseries	30/05/2022	
140	VIC	Carlsruhe		*B bison*	200	field nurseries	30/05/2022	
141	VIC	260Thirteen Mile Rd in Garfield		*B bison*	100	Field nursery	May-22	
142	VIC	Thirteen Mile Rd in Garfield		*B bison*	100	Field nursery	May-22	
143	VIC	Strathewen		*B bison*	200	field nurseries	30/05/2022	
144	VIC	French Island		*B bison*	200	Field nursery	May-22	
145	VIC	Steels Creek		*B bison*	200	field nurseries	May-22	
146	VIC	Treases Lane, Mirboo North		*B bison*	250	Field nursery	22/06/2022	
147	VIC	Thornbys Rd in Nerrena		*B bison*	250	Field nursery	22/06/2022	
148	VIC	French Island		*B bison*	200	Field nursery	1/06/2022	
149	VIC	345 Parish Rd in Longwarry		*B bison*	100	Field nursery	May-22	
150	VIC	Tynong North		*B bison*	100	Field nursery	May-22	
151	VOC	Gardiers Rd in Foster		*B bison*	250	Field nursery	22/06/2022	
152	VIC	East Turtons Rd in Turtons Creek		*B bison*	250	Field nursery	22/06/2022	
153	VIC	Falls Rd in Foster		*B bison*	250	Field nursery	22/06/2022	

No.	State	Location	Dung type	Species	Number released	Type of release	Date released	Field core Dates & results
154	VIC	Sth Gippsland Hwy, Toora		*B bison*	250	Field nursery	22/06/2022	
155	VIC	Woodleigh		*B bison*	250	Field nursery	27/06/2022	
156	VIC	Glen Alvie		*B bison*	250	Field nursery	27/06/2022	
Component 17 - G spiniger mostly June 2021, CSU releases								
157	NSW	Bowman		*G spiniger*	10	Field nursery	June 2021	
158	NSW	Belecky		*G spiniger*	10	Field nursery	June 2021	
159	NSW	Darbys Falls		*G spiniger*	10	Field nursery	June 2021	
160	NSW	Darbys Falls		*G spiniger*	10	Field nursery	June 2021	
161	NSW	Cowra		*G spiniger*	10	Field nursery	June 2021	
162	NSW	Gooloogong		*G spiniger*	16	Field nursery	June 2021	
163	NSW	CSU Wagga		*G spiniger*	107	Hoop house nursery	.,.2019	
Component 18 - 2021 mixture via CSU database								
164	NSW	CSU Wagga	cattle	O. vacca Moroccan	240	Field nursery	sept 2021	
165	NSW	CSU Wagga	cattle	O. vacca French	240	Field nursery	sept 2021	
166	NSW	CSU Wagga	cattle	O. vacca Moroccan	240	Field nursery 1.2 m X 1.2 m	sept 2021	
167	NSW	CSU Wagga	cattle	O. vacca Moroccan	240	Field nursery 1.2 m X 1.2 m	sept 2021	
Component 19 - D gazella (CSU release)								
168	WA	SW WA		*D gazella*	1500	Field nursery	when?	

8.3 Factsheet: Rearing instructions for partners

Cage set up

Step 1- Choose location for cages

Choose a flat sunny location with enough space to allow for the required number of dung beetle rearing cages. Allow 360-degree access to each cage for beetle maintenance tasks and provide adequate space between cages for maintenance tasks such grass mowing or weeding. A site with a plumbed water supply is ideal as cages will require occasional irrigation during hot, dry weather.

Step 2- Cage construction: soil holding container

Several cage designs can work, but two things are important: beetles need to be contained and the cage requires good drainage. Large cages made of a Nally Mega-bins (AIM sales, Griffith NSW) (1165 mm L x 1165 mm W x 780 mm H, Volume 755 L) have proven successful at CSIRO. Other large containers could be used such as intermediate bulk containers (IBCs), raised garden beds, or water tanks etc. Used container should not have previously contained hazardous materials. It should be noted that Mega-bins or IBCs are not designed to contain large volumes of soil and some deformation of the container will occur. Old or sun damaged plastic containers may not be suitable.

Step 3 – Cage construction: drainage

Good drainage is critical for rearing dung beetles. Holes will need to be drilled at the bottom of your chosen container (Figure 1). Enough holes are needed to provide sufficient drainage to prevent water logging. As mentioned above, Mega-bins and similar are not designed to contain soil. The weight of the soil presses down on the base causing it to deform. The base needs to be supported on bricks to limit the deformation and ensure drainage remains possible. A layer of shade cloth or permeable geotextile is placed on the bottom of the container to stop soil from falling through the drainage holes and reduce the chance of escape of deep tunnelling dung beetles.

Step 4 – Cage Construction: top covering

Containers will require a mesh covering, fastened sufficiently so that beetles can’t escape. A course weave low UV blocking white shade cloth is sufficient and readily available (Figure 2). A tarp or waterproof cover might need to be used periodically in wet weather to limit soils becoming waterlogged.

Figure 1. *Mega-bin illustrating the number and distribution of 4 cm holes drilled into the base to ensure good drainage. Left: inadequate number of holes caused water logging as the base deformed due to the weight of soil directing water to the centre, away from the holes, right: more holes were drilled to ensure good drainage across the base regardless of any deformation. Image source: CSIRO*

Step 5 – Cage construction: Soil medium

Soil medium is important for successful dung beetle rearing. Each species can have different preferences. For the species currently reared (*Onthophagus vacca* and *Onthophagus andalusicus*), a sandy loam has produced good results. The sandy loam can be mixed with grade 1 or 2 vermiculite to increase moisture retention. Tamp the soil in the container to ensure it is slightly compacted. Once the cage is filled with soil medium it is ready to use.

Figure 2. *Completed cages, left: welded aluminium angle frame, with a polycarbonate access door, clad in white shade cloth, right: cages covered with a piece of white shade cloth, fastened to cages by bulldog clips. Image source: CSIRO*

Step 6 – Feeding

To breed, dung beetles require a constant supply of dung. Beetles will need their dung supply to be replenished weekly with fresh dung or thawed frozen dung. The amount of dung depends on the number of beetles initially added to the cage and subsequent observed beetle activity. A minimum amount of dung to place in active cages is 3 litres per week (Figure 3). If feeding activity is high and the dung is shredded quickly, add another 3 litres or more. Beetles will be especially active during spring and summer. The beetles will breed in spring and the following generation will emerge over the summer. They will spend summer feeding and will not breed until the following spring after spending winter buried in the soil. Feeding activity reduces significantly in the late autumn and ceases during the winter. Placement of dung in the cages through this period can cease but will need to recommence in the late winter to feed the first spring emerging beetles. The exact timing of beetle activity will depend on local climate and seasonal weather conditions. Cage custodians will have to make their own observations on beetle activity and act accordingly.

***Figure 3**. Left: Dung pad with dung beetle activity, right: Onthophagus vacca dung pad shredding. Image source: CSIRO*

Step 7 – General maintenance: Watering

Soil moisture is an important factor in dung beetle rearing. If the soil becomes dry, the cage will need to be watered, an amount equivalent to a light-moderate rain event. Dung will also provide moisture, therefore do not overwater.

Step 8 – General maintenance

Successful dung beetle rearing requires constant monitoring and care. Cages should be checked weekly for the presence of spiders, ants, rodents and other organisms that can penetrate the cage and harm beetles. Larger animals such as birds, foxes, cows, sheep etc. should be excluded from the cage area as they could cause considerable damage to cages and harm beetles. Old dung should be regularly removed from the soil surface once the beetles have ceased using it. Old dung can be breeding sites for pest flies (sciarid flies) which can also feed and destroy dung beetle broods. The soil surface should be free of weeds. Maintain the outside areas of the cages, keep grass mown/slashed, to allow easy access and reduce fire risk

8.4 Farmer Nurseries Protocol: On-farm producer-managed field nurseries for Onthophagus vacca and other species

Bernard Doube, Paul Meibusch, Loene Doube
November 2019

1. Broad activity schedule

Step-by-step activities and their suggested sequence are detailed in the section 'Activities'.

The first stage of Farmer Nurseries, in spring-summer 2019, is already well under way and has four components:

1. **Spring 2019** (September)**:** French *O. vacca* nurseries, breeding beetles released
2. **Spring 2019** (October)**:** French *B. bubalus* nurseries, breeding beetles released
3. **Early summer 2019** (November): Moroccan *O. vacca* breeding beetles released
4. **Early summer 2019** (December): French *O. vacca non*-breeding beetles released.

The schedule for managing each of these four components is provided in the attached Gantt chart.

2. Rationale and summary

DBEE Theme 3 is required to release new dung beetle species at a minimum of 100 sites over the life of the project, with specific focus on *O. vacca, B. bubalus* and three additional imported species/strains. In order to begin this process in spring 2019, while managing the very real risk of beetle losses, the program intends to utilise a concept coined 'Farmer Nurseries', which is planned to be the primary route by which DBEE beetles are established on producer properties across southern Australia.

Farmer Nurseries, as the name implies, are local mass rearing facilities situated on carefully selected farms in target release regions selected using the current predictions about where the beetles are likely to best prosper (CLIMEX analysis). A pilot program with the French *O. vacca* and *Bubas bubalus* was established in September and October 2019. The program is being extended to include the release of Moroccan *O. vacca* (reared at CSIRO, Canberra) in November 2019 and a second cohort of French *O. vacca* in December 2019.

The volunteer collaborating producers will manage the nurseries during the 18-month course of the trial, and, if the Farmer Nurseries are successful, their property will receive an inoculum of some thousands of beetles. The producer will need to agree that a small proportion of the beetles produced may be removed from the trial in order to inoculate new nurseries in other locations.

The benefits of using this approach include:

- Smaller initial numbers of beetles than with the usual method of field release (commonly 1000+ beetles per release site) can be released to the field at each site, spreading risk and making the most of very limited beetle supplies.
- At successful sites the expectation is for reasonable multiplication of initial numbers, allowing for significant subsequent field releases and establishment of additional founder/starter colonies.
- Farmers will be encouraged to take ownership of the sites (under supervision of a program researcher) and provide much of the regular upkeep and maintenance.

- The approach allows DBEE to be in the field with farmers, delivering beetles a year earlier than anticipated and closer to the original planned schedule.
- Having multiple locations enables evaluation of the specific soil and climatic requirements of the new species before broad-scale release takes place.

The complete Farmer Nursery concept has three elements but not all elements have been established at all test sites. The complete nursery comprises:

- **On-ground rearing cages**: two on-ground 1 x 1 m beetle rearing cages, maintained under optimal conditions
- **An on-ground rearing arena**: a mass rearing arena under a 4 m x 5 m s sheet of 70% shade cloth
- **Dung+beetles-inoculated soil cores**: two soil cores inoculated with dung and beetles that will be used to assess the rate of development of the immature beetles under local field conditions. This will determine when trapping the beetles in the field cages needs to begin.

The first stageof Farmer Nurseries, in spring-summer 2019, is already well under way and has four components.

1. **Spring 2019:** French *O. vacca* nurseries, arenas and soil cores have been established in spring 2019 in all southern states. The beetles comprised one batch of 3,500 F_0 *O. vacca* from Creation Care. Beetles were placed in the field in September 2019 (in field cages, arenas and soil cores) at 26 locations across southern Australia. The trial will encompass two generations in the field (September 2019 to February 2021). The primary focus in spring 2019 was on cattle dung but horse and sheep dung are also being tested as food for the new beetle species (Table 1).
2. **Spring 2019:** French *B. bubalus* nurseries have been established in spring 2019 in SA and NSW. The beetles comprised 50 breeding *B. bubalus* from Creation Care. Beetles were placed in field cage is SA (n = 3) and NSW (n = 1) in October 2019 (Table 1). The trial will encompass two generations in the field (September 2019 to February 2021).
3. **Early summer 2019**: Moroccan *O. vacca* arenas are about to be established (mid-November 2019) in NSW (n = 2) and SA (n = 1). The beetles will comprise 1000+ breeding (post-vernalisation) F_1 *O. vacca* from CSIRO, Canberra. The F_1 beetles will be held under a large shade cloth arena (4 m x 5 m) and fed ample dung and maintained there until January 2020. The trial will encompass two generations in the field (September 2019 to February 2021). The beetles will be maintained there until the F_2 beetles emerge and feed and enter diapause and the go underground (probably in late autumn 2020). A separate protocol was developed for this component.
4. **Early summer 2019**: French *O. vacca* from Creation Care (n = 15,000 beetles, pre-vernalisation). On farm releases of F_1 *O. vacca* starter colonies (possibly 3000+ beetles per colony) in November–December 2019, on five properties as indicated by the performance of the cage beetles in spring (component 1). The F_1 beetles will be held under a large shade cloth arena and fed ample dung and maintained there until January 2020. The trial will encompass one generation in the field (December 2019 to February 2021).

Table 1:Spring 2019 allocation of on-farm Farmer Nurseries (Components 1 and 2)

	# states	Cattle dung	Sheep dung	Horse dung
Onthophagus vacca	5	26	3	2
Bubas bubalus	2	5	–	–

The validation of the field cage and arena techniques for promoting successful field establishment of *O. vacca* and *B. bubalus* will provide a model that should greatly improve the speed and probability of successful establishment of future introductions of new species. The arena technique, if successful, should substantially reduce the cost of establishing founder populations, due to lower material and labour costs at each release site as well as speeding up the spread of the beetles across southern Australia.

3. Background

The need to speed field establishments

The DBEE program suffered some initial setbacks with mass rearing of the French *O. vacca* and *B. bubalus* which caused significant delays in the projected supply of beetles for field releases.

Because of limited numbers of beetles available for field release and time constraints in the program schedule, it became clear that new methods to speed the delivery of beetles to the producers were necessary. This led to the development of the Farmer Nursery concept.

Beetle supply

There are two primary sources of dung beetles for the current project.

Creation Care Pty Ltd (a provider of environmental services in SA) has both French *O. vacca* and *B. bubalus* in successful mass rearing facilities. DBEE purchased a supply of both species for field release in spring–summer 2019. A portion of the DBEE spring-breeding *O. vacca* stocks have been retained for mass rearing in Perth, Armidale and Wagga.

Through CSIRO, DBEE is importing new strains and species of dung beetle from Europe. The Moroccan *O. vacca* is well established, with mass rearing occurring in Canberra and Wagga. In addition, small numbers of *B. bubalus* have been established in field nurseries in Canberra. Additional species are to be reared in Canberra and subsequently further multiplied in mass rearing facilities at Wagga and possibly Armidale. These will be used to establish field nurseries as a first step towards broad-scale establishment of the new species across southern Australia.

A supply of the new dung beetle species (either sent by air courier or delivered personally by DBSI staff) will be delivered to each test site.

Dung supply

The beetles in the cage nurseries need to be fed regularly from their introduction in spring through to mid-summer. This requires a substantial supply of high-quality dung.

The spring-active dung beetles that are currently being released are considered to be highly sensitive to dung quality. Dung quality varies throughout the year, with the highest quality being produced in spring by cattle grazing a good-quality green pasture (preferably a mixture of legume and grass). It is imperative that the cattle producing the dung for use in the trial have not been treated with beetle-toxic chemicals for two months before the dung is collected.

A substantial amount of dung needs to be collected in spring and held. In Canberra and Wagga, the dung has been frozen for storage. However, it is not practical for farmer-based beetle-rearing activities to freeze and store large quantities of dung.

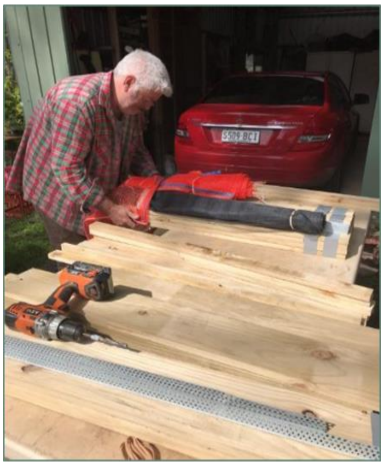
An alternative method is readily managed. Dung can be collected in spring, stored in large lidded bins for months without losing its usefulness as a high-quality food for dung beetles. The bins can be located at the trial site and the dung used as required. Dung stores well in such circumstances. As long as the dung is collected about a week before it is used, any contamination with field-collected beetles is unimportant because these beetles will have drowned in such circumstances.

The quantities of dung that need to be collected and stored will vary with the species being tested, its stage of development and the number of beetles in the cage or arena. For example, we estimate that the breeding French *O. vacca* (n = 170 approximately) released into Farmer Nurseries in September2019 will require up to about 130 litres, enough to supply the nurseries during spring–summer 2019–2020. We advise that this amount is best collected on-farm in spring and stored in large bins for use as required during that period. The dung needs to be collected about a week before setting up the trial in order to allow feral dung beetles collected accidentally to drown before the dung is added to the field trial.

Collecting and storing a substantial dung supply

Manufacture and delivery of field equipment

DBSI developed a flat-pack for the Farmer Nursery components (each comprising components for two field cages, a dung beetle arena and two soil cores). These were packed in Adelaide and dispatched by courier or by DBSI staff to farmers in WA, SA, Vic, Tas and NSW, where the nurseries have been assembled on-farm. Collaborators in WA, NSW and Tas had to source their own shade cloth for their arenas.



Assembling the flat packs (2 cages, 1 arena, 2 soil cores)

Assembling the cages

Men at work

In the SA and Vic locations, the assembly of the cages and the collection of the dung was a joint activity between the collaborating producer and DBEE staff. In WA, NSW and Tasmania, the collaborators did not have this assistance. However, construction of the cages and arena was straightforward and did not pose problems for the collaborators.

Progress to mid-November 2019

- Complete Farmer Nurseries (field cages, arenas and soil cores) for French *O. vacca* were established in WA, SA, Vic, NSW and Tas. in September 2019.
- Nurseries using only field cages were established for *B. bubalus* in NSW and SA in October 2019.
- Nurseries using field cages or arenas with cores were established for the Moroccan *O. vacca* in NSW and SA in November 2019.
- Plans for nurseries for the pre-vernalisation French *O. vacca* are in progress for a December 2019 release.

A small number of collaborators from outside DBEE but who are managing additional *O. vacca* or *B. bubalus* nurseries are also included in the project.

4. Methods

This section details the general procedures and materials. The required step-by-step activities and their scheduling are detailed in the section 'Activities'.

Choosing and preparing the test sites

Select a flat area from which stock can be excluded. The area for the cages and arena will be close-mown to minimise plant growth.

Before adding beetles and dung, the soil inside the cage and in the arena area will be lightly forked over to about 10 cm deep to soften the surface, making tunnelling easier for the beetles. This may not be necessary in locations with soft soil (e.g. sand).

Low soil moisture is considered to be a risk factor for larval survival of *O. vacca* in spring. To counter this possibility, the equivalent of 25 mm of rainfall (25 litres per 1 sq m cage) will be added to the cages and the central part of the arena (that destined for beetles) if the soil is dry or dryish and again in the first week of October and November (in addition to incidental rainfall).

Removing grass cover and forking the soil to soften it and facilitate tunnel construction

On ground rearing cages

At each location, two cages were set into a shallow trench about 5 cm deep and the inside edges of the cage trench were backfilled and trodden down to firm the soil and so prevent beetle escape.



Establishing the field cages

Component 1 (French *O. vacca* in breeding condition: released in September 2019)

At each field cage location, Cage 1 was inoculated with 50 F_0 breeding *Onthophagus vacca*. These F_0 beetles have been fed ample dung at weekly intervals and will continue breeding for 2–3 months. Egg-to-adult development takes 8–12 weeks (depending upon temperature) and so the F_1 beetles will begin emerging in late spring and will continue to emerge over the next 4–8 weeks. All of the F_1 beetles in Cage 1 will be trapped (see below for capture method), counted and transferred to Cage 2, where they will be fed dung until they stop feeding (probably in January–February 2020) and tunnel into the soil, where they will wait until spring 2020 to emerge again. It is likely that the F_1 beetles will begin emerging before all the parental F_0 beetles have stopped breeding, and so there will be a short period of overlapping F_0 and F_1 beetles in Cage 1. The optimal time to begin harvesting the F_1 beetles and transferring them to Cage 2 will be one week after they begin to emerge in Cage 1. There will be some contamination with F_0 beetles at that time. This cannot be avoided.

The number of F_1 beetles that emerge in Cage 1 (with an initial inoculum of 50 F_0 beetles) will provide a measure of the breeding success of *O. vacca* in that environment. For example, if 500 beetles emerge in Cage 1, then there will have been a 10-fold increase from one generation to the next generation.

These F_1 beetles (added to Cage 2 in late-spring / summer 2019–2020) will re-emerge from the soil over about 4–6 weeks in August–September 2020. These will be trapped, counted and 100 of them transferred back to Cage 1. The remainder will be added to the Arena.

High density of breeding beetles in the cages may be an important mortality factor (limiting breeding success) and so the number of breeding beetles per cage in spring 2020 will be limited to 100. All additional beetles will be transferred to the adjacent Arena. Once 100 beetles have been transferred to Cage 1, all remaining beetles that emerge will be transferred to the Arena.

The number of F_1 beetles that emerge in Cage 2 in spring 2020 compared with the number introduced to Cage 2 will provide a measure of the autumn–winter survival of the beetle in that environment. For example, if 500 beetles were introduced to Cage 2 and 400 emerged in spring 2020, then there will have been an 80% survival from late summer to spring.

Adding the dung at the northern end of the cage (L); *O. vacca* added to the dung (R)

Component 2 (B. bubalus in breeding condition: released in October 2019)

Field Nurseries for *B. bubalus* were established in spring 2019 in the following locations:

- Kangaroo Island SA, 16 beetles
- Barossa, 20 beetles
- Southeast of SA, 14 beetles
- CSU, Wagga, 12 beetles
- CSIRO Canberra, about 60 beetles.

The *B. bubalus* in field cages will need to be fed each week for possibly 3 or even 4 months (over spring and early summer 2019–2020) from their release in October 2019. Over one breeding season a pair in ideal conditions might bury up to 5 litres (= 5 kg) of dung. The adults will die once breeding ceases.

The next generation of adults will emerge in spring (probably August–September) 2020 and some may emerge in the same cage in spring 2021 (there being a possible 2-year life cycle in some locations). Emerging beetles should be collected, counted and transferred to a new field cage for breeding. As with *O. vacca*, high density of breeding beetles in the cages may be an important mortality factor and so the number of breeding *B. bubalus* per cage should be limited to no more than 10 pairs per square metre. Thus, additional cages may be required and will need to be built.

Overall at mid-November 2019, DBEE has a total of 138 adult *B. bubalus* in field cages. This may produce a thousand or more beetles in spring 2020.

Options for the management of these beetles include:

- retaining all beetles in the original locations for breeding the next generation
- retaining some beetles in the original locations for breeding the next generation and establishing satellite colonies with say 10 pairs per one square metre cage
- releasing all to the open field on collaborator properties.

It is essential that good records be kept outlining the procedures used at each location and the beetle production for the year 1 and year 2 (where there is a 2-year cycle) emerging beetles.

Summary for *B. bubalus*:

- Set up one cage in spring 2019 as for *O. vacca*, except that the cage needs to open to the west with the hinges to the east.
- Fork the soil and water if the soil is dryish, using 25 litres per sq m.
- Add two 2-litre dung pads at the western end of the cage.
- Watch dung burial activity and feed when necessary – always have moist dung present.
- I suggest feeding at weekly intervals, but monitor dung use and feed more often if required.
- Feed until burial ceases – probably about November–December 2019.
- Trap, collect and count the emerging beetles from Cage 1 in spring 2020 and spring 2021.
- In spring 2020 set up newly emerged beetles in field cages (up to 10 pairs per cage).
- Feed beetles during spring and early summer 2020.
- In spring 2021 trap, collect and consider what is best done with the beetles.

Table 2: Farmer Nursery sites for *Onthophagus vacca* and *Bubas bubalus* set up in spring 2019

	State		**Name**	**Dung type**	**Species**
1	WA	Geraldton, MIG	Rachel Mason	cow	*O. vacca*
2	WA	North Dandalup	Denise Honeybone	cow	*O. vacca*
3	WA	Lake Clifton	Gillian & Colin Vernon	cow	*O. vacca*
4	WA	Nannup	Bruce & Jane Wilde	sheep	*O. vacca*
5	WA	Wilga	Richard & Robyn Walker	cow	*O. vacca*
6	SA	Kangaroo Island	Linc Willson	cow	*O. vacca*
7	SA	Kangaroo Island	Linc Willson	cow	*B. bubalus*
8	SA	Barossa Valley	Michael Evans	cow	*O. vacca*
9	SA	Barossa Valley	Michael Evans	cow	*B. bubalus*
10	SA	Wrattonbully	Todd & Anne Woodard	cow	*O. vacca*
11	SA	Wrattonbully	Todd & Anne Woodard	cow	*O. vacca*
12	SA	Wrattonbully	Todd & Anne Woodard	cow	*B. bubalus*
13	SA	Port Elliot	Mark Higgins*	cow	*B. bubalus*
14	VIC	Cashmore	John & Dean Keiller	sheep	*O. vacca*
15	Vic	Tyrendarra	Phil Saunders	cow	*O. vacca*
16	VIC	Mitta Mitta	Judy Cardwell	horse	*O. vacca*
17	VIC	Mitta Mitta	Judy Cardwell*	horse	*O. vacca*
18	VIC	Mitta Mitta	Judy Cardwell*	cow	*O. vacca*
19	VIC	Mitta Mitta	Judy Cardwell*	cow	*O. vacca*
20	VIC	Mitta Mitta	Judy Cardwell*	cow	*O. vacca*
21	VIC	Mudgegonga	Chips & Grace Boucher	horse	*O. vacca*
22	VIC	Mudgegonga	Chips & Grace Boucher	cow	*O. vacca*
23	VIC	East Gippsland	Adam Tran	cow	*O. vacca*
24	VIC	Cooriemungle	Gavin & Catherine Sinclair	cow	*O. vacca*
25	VIC	Yarra Valley	Marianne & Ron Sawyer	horse	*O. vacca*
26	VIC	Yarra Valley	Marianne & Ron Sawyer	cow	*O. vacca*
27	NSW	Orange	Sally Kirby	cow	*O. vacca*
28	NSW	Old Bonalbo	Lindsay Johnston	cow	*O. vacca*
29	NSW	Wagga	Agasthya Thotagamuwa	cow	*B. bubalus*

30	TAS	Burnie	Tom O’Malley	cow	*O. vacca*
31	TAS	Hobart	Andrew Doube	cow	*O. vacca*

* collaborators but not part of the official DBEE project

Component 3 (Moroccan O. vacca in breeding condition: released in November 2019)

About 300 adult *O. vacca* from the Canberra mass rearing facilities are to be released at each of three locations (two in NSW, one in SA). A protocol for this part of the program is appended.

Component 4 (French O. vacca in non-breeding condition: released in December 2019)

About 15,000 beetles from Creation Care are planned to be released at a series of locations across southern Australia, possibly 3000 at each of 5 locations. A protocol for this part of the program is appended.

On-ground rearing arenas

A second element of the Farmer Nursery concept, termed a dung beetle Arena, will be installed at most locations. Each will comprise a large (4 m x 5 m) shade cloth sheet under which beetles will be provided with ample dung. The shade cloth will be pegged down. This method has been trialled with *Bubas bison* and worked well for that species. We expect that it will work well for *O. vacca* and other species.

The shade cloth arena serves the following purposes:

- to confine the beetles and so reduce or prevent their escaping. The cover prevents flight and so the beetles must walk to move under the arena.
- to protect the beetles from predation from fowls, crows, foxes etc.
- for *O. vacca*, to provide an environment in which the beetles are not subject to competition for dung and breeding space from the large numbers of summer-active beetles commonly present in December–January each year.

Before adding beetles and dung:

- Ensure a moderate supply of dung.
- If using field dung, collect it some days before setting up the trial.
- Store dung in covered bins or use thawed dung.
- Clear the vegetation from the area to ground level (using a whipper snipper).
- Lightly fork the arena soil to about 10 cm in order to soften the surface, making tunnelling easier for the beetles.
- Water the arena soil using about 25 litres per square metre.
- Insert **two** soil cores in double beetle-proof bags (to a depth of about 30 cm) near the centre of the arena (see photos).

Low soil moisture is considered to be a risk factor for larval survival of *O. vacca* in spring. To counter this possibility, the equivalent of 25 mm of rainfall (25 litres per 1 sq m cage) will be added to the central 1 sq m of the arena (poured through the shade cloth) in the first week of the months September, October and November (in addition to incident rainfall).

Removing grass cover and forking the soil to soften soil and so facilitate tunnel construction

Setting up the soil cores

Adding dung and beetles

- Add 10 beetles to the soil on top of each soil core (buried bags).
- THEN add about 2 kg (litres) of dung to each core/ bag (on top of the beetles).
- Leave the core top open (to allow beetles to leave once the dung has been used).
- Add two concentric doughnuts of fresh dung towards the centre of the arena.
- Add a pile of dung in the centre of the first doughnut (not shown in photo).
- Add the remaining *O. vacca* (approximately 300) to the dung pile in the centre of the central dung doughnut.
- Cover the arena with shade cloth and secure the edges.

Feeding and recording progress

- Feed the beetles at weekly intervals.
- When feeding the beetles, note the distribution of soil casts and inspect under dung pads for tunnels.
- Record that data.
- Add fresh dung on the outside edge of where the dung burial activity has been observed. (The doughnuts will gradually increase in diameter as weekly feeding progresses.)
- Check the soil moisture at 10 and 20 cm weekly; record data.
- If the soil is dry add water (25 litres per sq m).

In Component 1, one hundred breeding *O. vacca* were released into the centre of the central dung doughnut. The dung in the doughnuts will be periodically renewed to provide ample dung for the beetles from November 2019 to February 2020 (i.e. feeding both the F_0 breeding beetles and the F_1 progeny). Dung burial in each of the two concentric doughnuts will be monitored to assess the use of the dung under the arena.

Monitoring development of the next-generation (F_1) beetles

After 6 to 8 weeks the next generation of *O. vacca* (the F_1 beetles) should have developed to the pupal/adult stage.

- After 7–8 weeks extract the first soil core and check the stage of development of the immatures/adults in brood balls; photograph and record on paper what you find.
- After a further 3–4 weeks extract the second soil core and repeat the process; photograph and record on paper what you find.

Developmental stages of O. vacca (photos G. Dalton)

Feeding the F1 beetles

Feed them, initially along with feeding the F_0s, until the F_1s have all entered diapause, stopped feeding and tunnelled into the ground. Begin feeding again when the F_1s re-emerge in spring 2021.

Expected time schedule

- The Arenas will be set up and the beetles introduced in mid-November 2019.
- Beetles should feed and breed for two to three months (finishing in February 2020).
- F_1 beetles should begin emerging after about 8–10 weeks (early February 2020).
- The F_1s should continue to emerge for 6–10 weeks (until April).
- The F_1 beetles should feed for 2–3 weeks before entering a non-feeding diapause.
- The F_1s beetles should re-emerge in spring 2020.
- The F_1s will be fed under the Arena.
- The F_1s should live for 2-3 months.

The third generation (F_2 beetles)

The third generation (F_2s) will be expected to emerge in late spring 2021.

- The treatment of the F_2 beetles needs discussion. Possibilities include:
    - Feed the F_2 beetles under the arena in early summer 2021
    - Release the beetles to the local collaborator's property

In January–February 2020 the F_1 beetles will enter diapause (dormancy) and tunnel underground, where they will remain until the following spring, when they will emerge to feed and breed.

The Arena will be kept in place over autumn and winter. In August 2020 the F_1 beetles will begin to emerge from the soil under the shade cloth arena and will be provided with ample dung for breeding during the following spring. These beetles will breed and the F_2 beetles will emerge in November – December 2020. These will also be fed under the shade cloth arena (to protect them from competition for the summer beetles). In February 2021, after the F_2 beetles have finished feeding and have gone underground, the shade cloth arena will be lifted.

The release and establishment program will have then been completed.

Beetle populations under the shade cloth arena will not be sampled but details of dung burial activity will be recorded each time the arena is lifted to feed the beetles (initially once per week, but this may extend once every 2 weeks, depending on the rate of observed dung burial).

If there is a 10-fold increase per generation, then there will be 500 F1 beetles in the cages in summer 2019–20 and 1000 beetles under the arena. In the following year it is possible that there will be in the order of 15,000 F2 beetles forming the nucleus of the introduction to the collaborator property.

Inoculated soil cores

In addition to the mass rearing in cages and arenas, in spring of year 1 (2019), two beetle-proof soil cores (each inside a double mesh bag) will be established. The soil cores will be located in the centre of the arena inside the first doughnut under the shade cloth.

Each core will be set up as described in the section 'Activities'. A 30 cm deep hole will be dug, a mesh bag inserted and backfilled with the excavated soil. Beetles will be added to the top of the bag and then dung added. The bags will be left open so that the beetles can join their cousins in the arena once they have used the dung on the cores.

The soil cores will be sampled 8 and 12 weeks after inoculation. Egg-to-adult development takes 8–10 weeks in warm weather, and longer in cooler climates. The developmental stage of the immatures extracted from the soil cores will allow an estimate of when the first beetles of the next generation are due to emerge in Cage 1. Once tanned (mature) adults are observed it is time to start trapping the beetles in Cage 1. This developmental schedule will guide a decision about when to start harvesting the F_1 beetles from Cage 1.

Harvesting beetles from the cages

Newly emerged beetles will fly and crawl within the cages during the day (*O. vacca* is a day-flying species), with a strong tendency to move towards the light (in the north). Consequently *O. vacca* will tend to accumulate at the northern end of the cage. This is where the beetle traps are to be placed. *B. bubalus* flies at dusk and dawn and is expected to accumulate in the eastern and western ends of the cage (flying towards the light).

Each trap comprises a fly-wire mesh square (about 30 cm x 30 cm) placed in a slight depression in the soil in the cage and a layer of sieved sand is placed over the mesh. About 0.5 litres of dung is then placed on the sand near the middle of the mesh. . Keep the edges flat to the soil (with sand) so that beetles can walk to the dung.

In component 1, feeding will cease in the rearing cage and a trap will be installed. The timing of this transition will be determined by the stage of development of the beetles in the broods extracted from the soil cores. The presence of adults in the broods indicates the time of transition.

There will be one trap in each rearing cage (one per location). The beetles will fly and crawl to the dung on the trap and tunnel into the dung and into the sand beneath it. The beetles can be recovered by removing the pad and sieving the sand. Some beetles will remain in the dung pad so search through it for beetles before returning it to the field cage. A different (and possibly better) method for recovering beetles from dung is to put the dung and sand into a bucket of water and the stir for 30 seconds. The beetles will float to the surface and can be readily collected. The number caught in the trap will be recorded on each occasion. The (wet) sand can be replaced on the fly wire mesh and the traps rebaited. Leave the traps baited at all times and collect the trapped beetles once or twice per week. The collaborator will need to monitor this activity and adjust as appropriate. Once collected and counted, the beetles can be released into Cage 2, where they will be supplied with fresh dung. They will feed there for 2–4 weeks then go underground for 6 months and emerge again

This trapping methodology may need significant revision after initial testing. Please think about ways to improve it.

> The F_0 *O. vacca* will arrive in September 2019 and will need to be set up and fed in field Cage 1 immediately. The life-time dung requirement for F_0 spring-emerged pairs of breeding adult *O. vacca* (September–November inclusive) is about 0.75 litres. This is based on the assumption that one pair uses 15 ml of fresh dung to produce one brood, and each female produces 50 broods.
>
> The F_1 beetles are likely to emerge over 4–8 weeks (November–December 2019) and will be transferred from Cage 1 to Cage 2 each week from mid-November. We expect that newly emerged beetles will need to feed once or twice per week for 2–4 weeks after emergence and before tunnelling into the soil to wait for spring 2020. We estimate that each beetle may require about 40 ml of fresh dung during that time. This estimate is based on the assumption that each beetle will feed on four occasions (10 ml on each occasion).

The 2019 life-time dung requirement for F_0 beetles in Cage 1 (25 pairs of spring emerged beetles) is in the order of 20 litres and the F_1 beetles in Cage 2 will require a further 20 litres. The 2019–2020 dung requirement for the Arena (50 pairs) is in the order of 80 litres.

Feeding schedule

Proposed feeding schedule (may be adjusted in light of experience):

Component 1 (French *O. vacca* added September 2019)

- **Cage 1 (September to mid-November 2019).** Add 3 litres of dung (3 x 1 litre mounds) in each of the first two weeks and then 2 kg per week for as long as they continue breeding (maybe 10 weeks); i.e. about 22 kg of fresh dung over 10+ weeks. Adjust as seems appropriate, checking the rate at which the beetles use the dung supplied.
- **Cage 2 (mid-November 2019 to mid-February 2020).** Add 2 litres of dung each week for 10 weeks after the first beetles are added to Cage 2 (transferred from Cage 1). Adjust as seems appropriate.
- **Arena (September 2019 to mid-February 2020).** Setting up the dung doughnuts in order to feed the F_1 beetles in the arena will initially require about 20+ litres (in two concentric doughnuts) then extra dung every week while the F_0 beetles breed (maybe 10 weeks) and then for a further 10+ weeks while the F_1 beetles feed (mid-November 2019 to mid-February 2020). Adjust as seems appropriate.
- **Extraction of soil cores**

The feeding schedule for spring to early summer 2020 will parallel that for 2019 but the amounts of dung required will depend upon how many beetles are produced and survive to breed in spring 2020. We will have some idea of this in early summer 2019.

Input form collaborating producers

The contribution from the collaborating farmer-producers will be substantial.

- Set up the trial following the instructions in the Protocol. Assistance will be provided in some locations, and phone and email guidance is always available.
- During spring and early summer in 2019–20 the beetles in the field cages will need to be fed each week, initially in Cage 1 and then in Cage 2. Observing the rate of dung burial may cause the collaborator to alter the interval between feeding events.
- Beetles will need to be trapped in Cage 1, counted, and transferred to Cage 2 in November–December 2019.
- Beetles will need to be trapped in Cage 2 and transferred to Cage 1 in August–September 2020.
- Beetles will need to be trapped in Cage 1, counted and transferred to the Arena in November–December 2020.
- Dung will be collected on one occasion and stored for use during spring summer 2019–20.
- The amount of dung needed for spring–summer 2020 will be decided once the number of surviving beetles is known.

The reward for the producer will be the establishment of the new species on their properties (provided that the environment is suitable), but this reward is at least two years away from establishing the trial. These beetle introductions will have considerable value (the current asking price is $20 per beetle). A one-off payment of $500 per location established in year 1 will be made to the collaborator once the trial is established and running.

Supply of materials

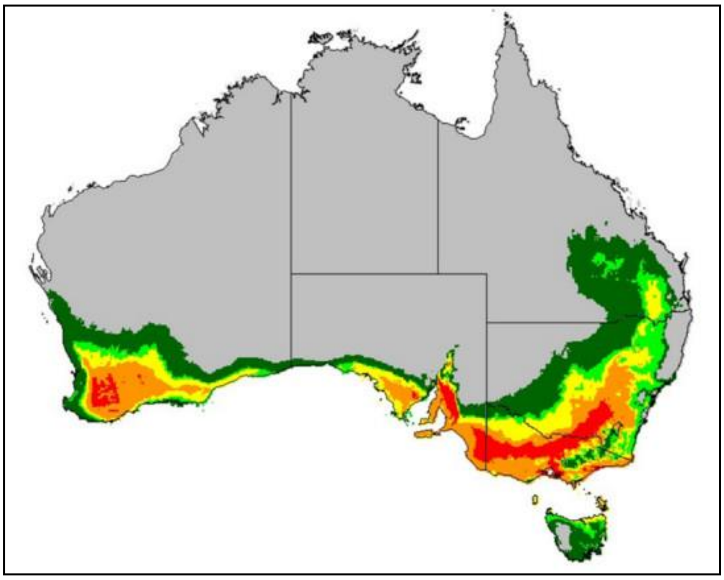
Cages will be supplied in flat-pack style and will need to be assembled on site. Timber cage panels will be pre-drilled and all screws and other materials for the cages supplied.

The collaborator may need to purchase bins for dung storage, shade cloth, a sieve and buckets for storing sieved dry sand (used in the traps).

Trial locations

The initial validation program will be conducted on a small number volunteer properties across southern Australia. The trial involves two generations of *O. vacca* and will take place over an 18–20-month period (September 2019 to February 2021).

Field releases of French *O. vacca* (September 2019) and *B. bubalus* are detailed in Table 2.



Potential distribution of *O. vacca* in Australia

5. Activities

Year 1 activities (2019–20)

Activities for each set of cages (2), cores (2) and an Arena at each location.

Spring 2019 (completed)

- Collect at least one bin full of dung, enough to set up the experiment, and store in a large covered bin about a week before setting up the cages and arena. If possible, collect 130 litres of fresh dung, enough for the whole field trial. Cap bins and deliver to test area.
- Purchase one 4 m x 5 m shade cloth sheet, and 8 or so tent pegs to secure it in place
- Select a site for the nurseries, large enough to house the two 1 m^2 cages and the 4 m X 5 m arena. Fence the area designated for the field trial.
- Close-mow grass in test area.
- Take delivery of flat-pack-cage and assemble cages
- Place cages and arena in the test area.
- Loosen the soil in both field cages and the arena (in the central area)to about 10 cm deep using a garden fork.
- Water soil if necessary.
- **Cage 1: September to November 2019**
  - Add three 1-litre dung pads at the northern end of the cage.
  - Add 50 dung beetles to the cage, dividing them between dung pads.
  - Close the lid and secure with bungee cords.
  - Add fresh dung (from the storage bins) each week.
  - Place new dung in a row adjacent (touching) to each previous dung pad, working from the open end of the cage to the hinge end.
  - If possible, record the proportion (roughly) of dung buried and the amount of dung added each week.
- Establish the Arena with dung doughnuts and dung beetles and soil cores with dung and beetles as follows:
  - Trace an oval shape about 2 m X 1.5 m near the centre of where the shade cloth will be secured.

- For the soil cores, excavate (using a shovel or auger) a 25 cm deep hole (about 25 cm in diameter) in the ground. Save the soil.
- Place a mesh bag into each hole and backfill it with the excavated soil.
- Add 10 beetles to the top of the soil in each mesh bag.
- Add 1 litre of dung on top of the beetles.
- Do not seal the bag, but roll down the sides so that the open bag top is about 4 cm above the soil surface.
- Once the soil cores are in place, but before adding the beetles, place an oval of fresh dung around the soil cores along the traced outline.
- Place another oval of fresh dung about 50 cm away from the first oval.
- Release 100 *O. vacca* into the centre of the smaller dung doughnut, and 10 each onto the dung on the soil cores.
- Cover the entire arena with the shade cloth and secure with tent pegs or other means.
- Monitor the amount of dung in the arena often and add extra dung when needed.
- Do not add extra dung to the soil cores.
- Feeding with fresh dung can stop when beetles stop feeding, in January or February 2020.

The beetle-proof soil cores will be inoculated and sampled on two occasions to identify the timing of emergence of the next generation of beetles in late spring.

Egg-to-adult development in spring takes 8–10 weeks in warm environments and considerably longer in cool environments. In both situations newly emerged F1 beetles will appear before the F0 beetles have finished breeding, i.e. the two generations will overlap to some extent. This creates sampling problems. The F1 beetles need to be collected and counted and moved to their new field cage (Cage 2) but checking each beetle to assess the degree of tibial wear (the tibia become worn out (eroded) in older beetles) is impractical and so we need to know when the first F1 beetles are about to emerge (8–16 weeks after breeding first occurs). This information will be provided by documenting the developmental stages present in the broods recovered (by sieving) from the beetle-proof soil cores after 8 and 12 weeks. This will allow us to minimise the number F0 beetles collected in late spring (thereby maximising their reproductive potential) and minimising F0 contamination of the estimate of the number of F1 beetles emerging.

- To sample the soil cores:
  - Sample one soil core after 8 weeks and another at 12 weeks.
  - Remove the soil core from the soil in the Arena and place on a table or the like.
  - Cut the bag open along one side and the bottom to reveal the soil core.
  - Open the soil core and find any broods (small round dung packages) in the soil.
  - Collect 15 broods and break them open and record the developmental stage of the occupant of each brood (larva, pupa, untanned adult, tanned adult).
  - Record empty broods and any dead individuals present, and their stage if possible.
  - Replace the remaining unopened broods in the hole from which the core was removed and gently replace the soil.
- In November–December (the timing indicated by the presence of tanned adults in the cores), begin to trap beetles in Cage 1 at weekly (or twice weekly) intervals as follows:
  - In the morning, place three sheets (approx. 30 cm x 30 cm) of plastic fly wire (or the equivalent) adjacent to each other on the ground against the northern inside edge of the cage.
  - Pour and spread sieved sand over the central part of each sheet to a depth of about 25–30 mm.
  - Place a dung pad of about 0.5 litres of fresh dung on the sand in the middle of each sheet.

- After a few days or a week , carefully remove the dung and search through it carefully before discarding it.
- Count any *O. vacca* recovered in each pad and record the numbers.
- Place the sand from each trap in a sieve; retrieve and count the beetles, and record the numbers.
- Some beetles may fall through the sieve so keep an eye on the surface of the sand in the sieve and pick up any escapees. Count and record these as well.
- Transfer all counted beetles to Cage 2 (see below).

-
- Begin feeding beetles in Cage 2.

- **Cage 2: November 2019 to February 2020**
  - Once beetles have been trapped from Cage 1 but before transferring them to Cage 2, add three 1 litre dung pads at the northern end of Cage 2.
  - Add the dung beetles harvested from Cage 1, dividing them between dung pads.
  - Close the lid and secure with bungee cords.
  - Add fresh dung (from the storage bins) each week as required.
  - Place new dung adjacent (touching) each previous dung pad.
  - Record the amount of dung added and the proportion (roughly) of dung buried
  - Add 25 litres water to the soil in the cages at the beginning of **each** month (December through to March J).

Year 2 activities (2020–21)

The timing of emergences and feeding periods in year 2 have been assumed to be similar to those observed in year 1. These will vary between locations by 4–8 weeks depending upon temperature.

- All four field cages managed according to 'best-practice' (to optimise production) as specified by the instructions from Creation Care
- Beetles from Cages 3 and 4 will emerge over about 4 weeks in spring 2020 and will be trapped and counted.
- Beetles that emerge from Cages 3 and 4 over weeks 1 and 2 will distributed equally between Cages 1 and 2.

- The remaining emergences (emerging over weeks 3 and 4) will be will be accumulated in plastic containers with soil and dung and then returned to Cages 3 and 4 at the end of the fourth week. Divide beetles equally between Cages 3 and 4.
- Beetles in all four cages are expected to breed optimally
- In late spring / early summer the F2 beetles will emerge over about 6 weeks
- The F2 beetles will be trapped and counted (absolutely essential) and then released to the field under protective shade cloth where they will be fed fresh dung (under the shade cloth) until they enter diapause and tunnel underground. Feeding may be required over 4-8 weeks. The shade cloth is necessary to protect the F2 beetles from severe competition from the summer beetles that will emerge in December –January.
- This could lead to a late-spring-summer release of 5,000 to 10,000 F2 beetles per property after 18 months.

6. Materials

The material requirements for each test location are as follows:

data sheets for recording beetle performance

- Two field cages
- One Arena
- Materials to construct 2 soil cores (auger, mesh bags)
- 50 *Onthophagus vacca* for Cage 1
- 10 *O. vacca* for each of two soil cores (n = 20)
- 100 *O. vacca* for the Arena
- Large bins in which to store dung
- Shovel and trowel for collecting dung
- Dung measure (1 litre)
- Bucket for sieved sand
- Sieve (fine) for separating beetles from sand
- 6 beetle traps
- Water container for monthly watering (20 litres per cage)

Field Arena

- Sheet of shade cloth
- tent pegs (n=8)
- 100 *Onthophagus vacca*
- Large bins in which to store dung
- Shovel and trowel for collecting dung
- Dung measure
- mesh bags for field cores (n=4, used double)
- Sieve (coarse) for extracting broods from soil core

Flat pack materials for two nurseries (all supplied)

- Four shorter and two longer wooden lid sides – pre-drilled
- Four shorter and two longer wooden box sides – pre-drilled
- 16 screws for ends of lid/side planks
- two 1 x 1 m sheets of gauze

- 24 nails to hold gauze in place before fixing with angle iron
- Four shorter and two longer pieces of angle iron
- 32 screws to hold down angle iron
- 6 m of sealing tape
- four hinges
- 12 hinge screws
- four pieces of bungee cord
- four screws/hooks to attach to bungee cord

7. Labour requirements

The labour requirements for each location are as follows:

- Spring–Summer Year 1
    - Regular supervision of collaborators
    - Scientific training of collaborators
    - Scientific assistance to set up initial trial
    - collecting and store dung supplies in large buckets
    - assemble 40 field cages
    - Set up the 40 field cages
    - add beetles and dung to Cage 1
    - set up 40 field cores with dung and beetles (1 litre dung+ 10 beetles)
    - weekly or biweekly checking and recording levels of dung burial in Cage 1 and Arena
    - Regular dung additions to Cage 1 September to early November
    - Stop adding dung to Cage 1 in Cage 1 early November
    - Sample one field core late-October (week7 – 8)
    - Dissect up to 15 broods to assess stage of development: record all data
    - Sample one field cores late November (11–12 weeks)
    - Dissect up to 15 broods to assess stage of development: record all data
    - Keep data for each soil core separate
    - Begin bi-weekly baiting traps in Cage 1 as indicated by data from soil cores
    - Trap, count and record beetle numbers from beetle traps
    - After counting, add e beetles to Cage 2
    - Regularly weekly) feed beetles in Cage 2
    - Continue adding beetles to Cage 2
    - Continue feeding until dung is no longer consumed.
- Spring–Summer year 2
    - collecting and store dung supplies in large buckets
    - Mid July place dung pads I litre per field cage 2
    - check for beetles and tunnels after 1 week
    - Remove uneaten old pad: add fresh dung
    - Continue removing uneaten pad and adding fresh pad at weekly intervals
    - Begin bi-weekly baiting of traps once the first *O. vacca* emerge
    - This may be August in warm climates and September–October in cool climates
    - Trap, count and record beetle numbers from each pitfall trap
    - After counting, add beetles to Cage (up to 100 beetles) 1
    - Regularly (weekly) feed beetles

- Continue to trap, count and record numbers from traps in Cages2 and transfer beetles (if >100 emerge) to the Arena
- Continue feeding Cages 1, until dung the beginning of November
- weekly checking and recording levels of dung burial
- Stop feeding beetles in Cages 1 in early November

8. Additional O. vacca-specific issues

Danger points in the seasonal biology of Onthophagus vacca

Adults of *Onthophagus vacca* emerge in spring to breed having spent the past 6 months underground in a reproductive diapause (arrested development). The timing of the spring emergence appears to vary from late-July–August in warm environments (eg Strathalbyn) to September–October in cooler regions (e.g. Port Elliot at the southern tip of the Fleurieu Peninsula).

Adult F0 beetles emerge over a period of about 4 weeks. They feed for 1–2 weeks before beginning to breed. Broods are placed in tunnels beneath the dung pad and are usually located 10–20 cm below the soil surface. Breeding continues for 2–3 months: the F0 adults then die. A generation-to-generation increase of 15-fold has been achieved in nurseries (ie an average of 30 surviving broods per female). Egg to adult takes 8–12 weeks (depending upon temperature). The earliest F1 adults emerge while the F0 parents are still breeding and so two generations overlap for some weeks in early summer. The F1 adults feed but do not breed (a feeding non-breeding diapause). Feeding continues for some weeks (producing fat body for energy storage) then they tunnel underground where they remain until emerging in spring to breed. Some may make a visit to the soil surface to feed (but not to breed) during autumn.

The danger points in the life cycle of O. vacca in the field are

- Spring breeding for F0 adults
  - dung supply
  - dung quality for breeding beetles in spring (poor dung quality reduces fecundity)
  - soil conditions that allow breeding (soil may be too hard to tunnel into)
  - beetle density (crowding may reduce fecundity per female)

- Survival of F1 immatures
  - soil conditions that allow egg–adult survival (moisture conditions: too wet, too dry)
  - brood density (crowding may reduce survival)

- Early summer emergence and feeding for F1 adults
  - dung supply
  - dung quality for feeding beetles in spring (poor dung quality may reduce fat body production er extend the time required for fat body production)
  - competition with other summer active beetle species (reducing availability of food for the newly emerged adults)
  - soil conditions that allow feeding (soil may be too hard to tunnel into)
  - soil conditions that allow tunnelling to depth (soil may be too hard to tunnel into)
- summer to spring – in diapause deep in the soil
  - physical conditions (to wet, too dry too hot).

In addition, Creation Care had about 2000 adult B. bubalus in spring 2019.
The protocol for the *B. bubalus* has not yet been drafted but in essence the following will apply.

The *B. bubalus* need to be fed in spring and early summer 2019 in one field cage. The adults will die once breeding ceases. Over one breeding season a pair in ideal conditions might bury up to 5 litres (=kg) of dung. The next generation of adults will emerge in spring (probably August-September) 2020. Some may emerge in the same cage in spring of 2021 (a 2-year life cycle). The new beetles need to be counted and set up in new nurseries with up to 10 pairs per 1 x 1 metre nurseries. This may require a number of nurseries. If the 12 beetles generate near a 10 fold increase (a top result), then you may need 5 or 6 extra nurseries in spring 2020. Feed them in spring and early summer of 2020. Capture next generation in spring of 2021 and consider public release(under arenas). We will use cages only, not arenas, in the first instance.

9. Summary

- Set up one cage in spring 2019 as for *O. vacca*, except that the cage needs to open to the west with the hinges to the east.
- Don’t forget to fork the soil and water if the soil is dryish 25 litres per sq m = 25 mm (before adding the dung and the beetles)
- Start with two 2 litre dung pads at the western end of the cage
- Watch dung burial activity and feed when necessary - always have moist dung present
- Suggest feeding at weekly intervals
- Feed until burial ceases - probably about Nov-Dec
- Trap collect and count the emerging beetles from cage 1 in spring 2020 and spring 2021
- In spring 2020 set up newly emerged beetles in field cages (up to 10 pairs per cage).
- Feed beetles during spring and early summer of 2020
- Spring 2021 Trap, collect and consider what is best done with the beetles
- Best option id local release on collaborator properties, where appropriate
- Two generations could generate 1000+ beetles with a 10-fold increase per generation – a very good start

8.5 Results of on farm producer nursery experiment

Twenty two farmer nurseries were initially established using cow dung (n = 17), sheep dung (n = 3) and horse dung (n=2) . Additional nursery sites (52) sites were established as participants joined and were fed with the dung most available on the producer's property. Nurseries were established across a range of climates, from hot and dry (Geraldton, WA), subtropical (Old Bonalbo, NSW) to cool and wet (Portland Vic and Burnie, Tas).

The principal findings in relation to *O. vacca* are as follows:

- Successful field nurseries were established in all southern states/territories (ACT, WA, VIC, NSW, Tas, SA).
- *O. vacca* bred successfully in cow, sheep and horse dung.
- Generation-to-generation increases (up to 6-fold) were in line with that observed in the highly successful nurseries in MLA project ERM 0216.
- Beetles bred in field cores in the hot dry conditions where immature development was rapid (estimated egg-to-adult 8–10 weeks) but the immatures failed to survive.
- The soil core data indicated that egg-to-adult development could take from 8 weeks to 16+ weeks.
- The emergence of F_1 adults in cages showed that egg-to-adult development took 10–12 weeks in temperate warm conditions however some cool climates revealed 5-7 months egg-adult periods while others such as the ACT were consistent with the expected lifecycle of 10-12 weeks observed elsewhere. This was unexpected.
- Where egg-to-adult development took 6–7 months (e.g. Cooriemungle, Vic), the breeding adults still emerged in spring (September), albeit a month later than in warmer climates. The interval underground was therefore correspondingly shorter in cool climates (4 months) compared with that in warmer climates (8–9) months.
- The level of survival of the diapausing adults underground was highly variable. The factors affecting survival are unknown and the current data does not allow an association to be drawn between duration underground and the level of survival.

In addition, 50 *B. bubalus* were purchased and used to establish five field nurseries in South Australia in October 2019 with 10 breeding adult each. Two of these appear to have produced significant numbers of offspring, while the others failed. In one successful nursery at the southern end of the Fleurieu Peninsula, SA the emerging F_1 beetles were counted and in this case 8 F1 beetles emerged in spring 2020 and 53 F1 beetles emerged in spring 2021, producing 61 beetles from 10 breeding adults. In the second nursery, on Kangaroo Island, the beetles were retained in the nursery for two years then released but were not counted. In both situations few offspring emerged in year one with the majority emerging in spring of year 2, demonstrating that in cool climates *B. bubalus* exhibits a 2-year life cycle. It is possible that the species will have established from this small beginning, but this cannot be ascertained for 5–10 years.

8.6 Supporting information for application to Live Import List

Information supporting the application to amend the List of Specimens Suitable for Live Import to include fourteen new species of dung beetles (Coleoptera: Scarabaeidae and Geotrupidae) as suitable for import and for release

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December 2021

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Rationale

This proposal provides information supporting the application to amend the List of Specimens Taken to be Suitable for Live Import to include fourteen species of dung beetles (*Geotrupes stercorarius, Ateuchetus laticollis, Cheironitis scabrosus, Copris incertus, Copris integer, Copris lunaris, Euoniticellus triangulatus, Gymnopleurus humanus, Onitis minutus, Onthophagus medius, Onthophagus nuchicornis, Onthophagus opacicollis, Scarabaeus sacer* and *Sisyphus schaefferi*) as suitable for importation.

The objective of introducing these species is to enhance dung burial and bush fly control in the major sheep, beef and milk producing areas of Australia to fill existing seasonal and geographical gaps in dung beetle activity.

Adult beetles will be collected from various locations in Europe, Africa and New Zealand, and air-freighted to Australia. The beetles will be handled similarly to the previous projects in the early 1990s, 2011-2015 and 2018-current. Briefly, in-coming adult beetles will be held in an Approved Arrangements site (AA) in a quarantine facility in Canberra. Their eggs will be treated with disinfecting agent (Virkon®), removed from quarantine, reared to adulthood, and used for the establishment of mass-rearing colonies, the progeny of which will be released. Release sites will be chosen by selecting climatically optimal sites on properties whose owners are committed to doing everything necessary to maximise the beetles' establishment, such as avoiding the use of parasiticides. Beetles will be released when they are sexually mature and physiologically synchronised with the local season. Release numbers will vary according to the numbers reared, but at any given site the aim will be to release a minimum of 500 male-female pairs of each species.

1. Taxonomy

All dung beetles fall under the same classification, up to family.

Phylum: Arthropoda

Class: Insecta

Order: Coleoptera

Table 1 provides information on the taxonomy of each of the species, beginning with family. It includes synonyms, subspecies and a taxonomic reference.

Table 1. Taxonomy of selected species

Family	Genus	Species	Synonyms and Subspecies	Taxonomic Reference
Geotrupidae	*Geotrupes*	*stercorarius* (Linnaeus, 1758)	*Geotrupes bannani* Bromfield, 1834 *Geotrupes chalybaeus* Mulsant, 1842 *Geotrupes exaratus* Mulsant, 1842 *Geotrupes fimicola* Mulsant 1855 *Geotrupes intermedius* Ferrari, 1852 *Geotrupes juvencus* Mulsant, 1842 *Geotrupes punctatostriatus* Stephens, 1830 *Geotrupes punstatostrius* Stephens, 1830 *Geotrupes putridarius* Erichson 1848 *Geotrupes stercorarius* subsp. *chalybaeus* Mulsant, 1842 *Geotrupes stercorarius* subsp. *exaratus* Mulsant, 1842 *Geotrupes stercorarius* subsp. *juvencus* Mulsant, 1842 *Geotrupes stercorarius* subsp. *quartanarius* Costa 1853 *Geotrupes stercorarius* subsp. *subrugulosus* Mulsant, 1842 *Geotrupes stercorarius* subsp. *subviolaceus* Mulsant, 1842 *Geotrupes subrugulosus* Mulsant, 1842	[1]

Family	Genus	Species	Synonyms and Subspecies	Taxonomic Reference
			Geotrupes subviolaceus Mulsant, 1842 *Geotrupes virescens* Mulsant, 1842 *Geotrypes stercorarius* subsp. *montanus* Olsoufieff, 1918 *Scarabaeus foveatus* Marsham, 1802 *Scarabaeus foveolatus* Marsham, 1802 *Scarabaeus stercorarius* Linnaeus, 1758	

Family	Genus	Species	Synonyms and Subspecies	Taxonomic Reference
Scarabaeidae	*Ateuchetus*	*laticollis* (Linnaeus, 1767)	*Ateuchus laticollis* subsp. *semilunatus* Xambeu, 1893 *Ateuchus semilunatus* Xambeau, 1893 *Copris serratus* Fourcroy, 1785 *Copris serratus* Geoffroy, 1785 *Scarabaeus alluaudi* Théry, 1932 *Scarabaeus laevicollis* Mulsant, 1842 *Scarabaeus laticollis* Linnaeus, 1767 *Scarabaeus laticollis* subsp. *alluaudi* Thery, 1932 *Scarabaeus laticollis* subsp. *laevicolli* Mulsant, 1842 *Scarabaeus laticollis* subsp. *minor* Seabra, 1907 *Scarabaeus laticollis* subsp. *striatopunctatus* Leoni, 1910 *Scarabaeus laticollis* subsp. *striolatus* Reitter, 1892 *Scarabaeus minutus* Seabra, 1907 *Scarabaeus serratusm* (Geoffroy, 1785) *Scarabaeus striolatus* Reitter, 1893	[2; 3]
	Cheironitis	*scabrosus* (Fabricius, 1776)	*Scarabaeus apelles* Fabricius 1781 *Scarabaeus scabrosus* Fabricius, 1776	[4]
	Copris	*incertus* Say, 1835	*Copris procidua* Say, 1835 *Corpus incertus* Say, 1835 *Corpus incertus* subsp.*incertus* *Corpus incertus* subsp.*prociduus* Say, 1835	[5]

Family	Genus	Species	Synonyms and Subspecies	Taxonomic Reference
	Copris	*integer* Reiche, 1847	*Copris pronus* Gerstaeker, 1884 *Copris troglodytarum* Roth, 1851	[6; 7]
	Copris	*lunaris* (Linnaeus, 1758)	*Copris belisama* Schrank, 1798 *Copris castaneus* Mulsant, 1842 *Copris corniculatus* Mulsant, 1842 *Copris deletus* Mulsant, 1842 *Copris gistelianu* Gistel, 1857 *Copris jenisonianus* Gistel, 1857 *Copris lunaris subsp. castaneus* Mulsant, 1842 *Copris lunaris subsp. corniculatus* Mulsant, 1842 *Copris lunaris subsp. deletus* Mulsant, 1842 *Copris lunaris subsp. obliteratus* Mulsant, 1842 *Copris obliteratus* Mulsant, 1842 *Scarabaeus belisama* Schrank, 1798 *Scarabaeus bifidus* Poda, 1761 *Scarabaeus emarginatu* Olivier, 1789 *Scarabaeus lunaris* Linnaeus, 1758	[8]
Scarabaeidae	*Copris*	*lunaris* (Linnaeus, 1758) (continued)	*Scarabaeus lunus* Schrank, 1798 *Scarabaeus quadridentatus* De Geer, 1778	[8]
	Euoniticellus	*triangulatus* (Harold, 1873)	*Oniticellus triangulatus* Harold, 1873	[9]
	Gymnopleurus	*humanus* MacLeay, 1821	*Gymnopleurus modestus* van Lansberge, 1886 *Gymnopleurus modestus* Péringuey, 1888 *Gymnopleurus peringueyi* Shipp, 1895 *Gymnopleurus sericatus* Erichson, 1843 Gymnopleurus *sericatus* var. *modestus* (van Lansberge) *Gymnopleurus humanus* var. *modestus* (Péringuey, 1888)	[10; 11 p278; 12]
	Onitis	*minutus* Lansberge, 1875		[11 p372; 13]

Family	Genus	Species	Synonyms and Subspecies	Taxonomic Reference
	Onthophagus	*medius* (Kugelann, 1792)	*Copris affinis* Sturm, 1800 *Copris medius* Kugelann, 1792 *Onthophagus confluens* Gistel, 1857 *Onthophagus vacca* subsp. *basalis* Mulsant, 1842 *Onthophagus vacca* subsp. *intermedius* Mulsant, 1842 *Onthophagus vacca* subsp. *propinquus* Mulsant, 1842 *Onthophagus vacca* subsp. *sublineolatus* Mulsant, 1842 *Onthophagus vacca* subsp. *vicinus* Mulsant, 1842	[14]
	Onthophagus	*nuchicornis* (Linnaeus, 1758)	*Copris acornis* Geoffroy, 1785 *Onthophagus alpinus* Kolenati, 1846 *Onthophagus dillwyni* Stephens, 1830 *Onthophagus immaculatus* Mulsant, 1842 *Onthophagus indistinctus* Mulsant, 1842 *Onthophagus nuchicornis subsp. asimmetricus* Negrobov, 2003 *Onthophagus nuchicornis subsp. elenius* Negrobov, 2003 *Onthophagus nuchicornis subsp. immaculatus* Mulsant, 1842 *Onthophagus nuchicornis subsp. indistinctus* Mulsant, 1842 *Onthophagus nuchicornis subsp. rubripes* Mulsant, 1842 *Onthophagus nuchicornis subsp. rufipes* Negrobov, 2003 *Onthophagus nuchicornis subsp. submarginalis* Sahlberg, 1926 *Onthophagus nuchicornis subsp. vulneratus* Mulsant, 1842 *Onthophagus rhinoceros* Melsheimer, 1845 *Onthophagus rhinocerus* Melsheimer, 1846 *Onthophagus rubripes* Mulsant, 1842 *Onthophagus submarginalis* Sahlberg, 1926 *Onthophagus vulneratus* Mulsant, 1842 *Scarabaeus nuchicornis* Linnaeus, 1758	[15]

Family	Genus	Species	Synonyms and Subspecies	Taxonomic Reference
Scarabaeidae	*Onthophagus*	*nuchicornis* (Linnaeus, 1758) (continued)	*Scarabaeus planicornis* Herbst, 1789 *Scarabaeus trituberculatus* Schrank, 1798 *Scarabaeus verticicornis* Fabricius, 1775 *Scarabaeus xiphias* Fabricius, 1792	[15]
	Onthophagus	*opacicollis* Reitter, 1892	*Onthophagus schatzmayeri* Pierotti, 1959 *Onthophagus schatzmayeri* subsp. *fumatus* Schaefer, 1965 *Onthophagus schatzmayri* Pierotti, 1959	[16]
	Scarabaeus	*sacer* Linnaeus, 1758	*Ateuchus acuticollis* Motchulsky, 1849 *Ateuchus clypeatus* Motchulsky, 1849 *Ateuchus europaeus* Motchulsky, 1849 *Ateuchus impius* Fabricius, 1801 *Ateuchus platychilus* Fischer von Waldheim, 1823 *Ateuchus retusus* Brullé, 1832 *Ateuchus sacer* (Linnaeus, 1758) *Ateuchus sacer* subsp. *peregrinus* Kolbe, 1886 *Scarabaeus confluidens* Fleischer, 1925 *Scarabaeus crenatus* Degeer, 1778 *Scarabaeus degeeri* MacLeay, 1821 *Scarabaeus dufresneri* MacLeay, 1821 *Scarabaeus dufresnii* MacLeay, 1821 *Scarabaeus edentulus* Mulsant, 1842 *Scarabaeus europaeus* Motschulsky, 1849 *Scarabaeus impius* Fabricius, 1801 *Scarabaeus inermis* Mulsant, 1842 *Scarabaeus peregrinus* Kolbe, 1896 *Scarabaeus rufipes* Seabra, 1907 *Scarabaeus sacer* subsp. *confluidens* Fleischer, 1925 *Scarabaeus sacer* subsp. *edentulus* Mulsant, 1842 *Scarabaeus sacer* subsp. *inermis* Mulsant, 1842 *Scarabaeus sacer* subsp. *rufipes* Seabra, 1907 *Scarabaeus spencii* MacLeay, 1821	[17]
Scarabaeidae	*Sisyphus*	*schaefferi* (Linnaeus, 1758)	*Copris arachnoides* Fourcroy, 1785 *Scarabaeus longipes* Scopoli, 1763 *Scarabaeus schaeffer* Linnaeus, 1758	[18]

Family	Genus	Species	Synonyms and Subspecies	Taxonomic Reference
			Sisyphus capensis Gory, 1833 *Sisyphus schaefferi* subsp. *boschniaki* Fischer von Waldheim, 1823 *Sisyphus schaefferi* subsp. *minutus* Seabra, 1907 *Sisyphus schaefferi* subsp. *morio* Arrow, 1909 *Sisyphus schaefferi* subsp. *schaefferi* (Linnaeus, 1758) *Sisyphus schaefferi* subsp. *subemarginatus* Mulsant, 1842 *Sisyphus schaefferi* subsp. *subinermis* Mulsant, 1842 *Sisyphus tauscheri* Fischer von Waldheim, 1823	

1.1 Common Names

Common English names for species that have them are as follows:

- *Ateuchetus laticollis* is also known as the scarab dung beetle [19]
- *Geotrupes stercorarius* is also known as the dor beetle, dung beetle or lousy watchman beetle in the United Kingdom [20; 21]
- *Copris incertus* is known as the black dung beetle or uncertain dung beetle in Hawaii [22]; and is referred to as the Mexican dung beetle in New Zealand [23; 24]
- *Copris lunaris* is also called the horned dung beetle [25-27]
- *Onthophagus nuchicornis* is also known as the small black and brown dung beetle [28]
- *Scarabaeus sacer* is also known as the sacred scarab beetle [29 p133]

1.2 Genetic modification

None of the species have been genetically modified or engineered.

2. Status of species under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)

None of the selected species are listed on any of the CITES appendices. Four species were found on the IUCN Red List of Threatened Species, all ranked as of Least Concern. A summary of these species is provided in Table 2.

Table 2. Species on IUCN Red List of Threatened Species

Species	Assessment Date	Notes	Reference
Ateuchetus laticollis	22 July 2014	Wide distribution, locally abundant subpopulations	[3]
Cheironitis scabrosus	30 July 2013	Widely distributed in southwest southern Africa; regularly found in cattle dung; unlikely to be threatened as farming is common in its range	[30]
Gymnopleurus humanus	30 July 2013	Dominant member of assemblages within its range; found with a wide range of dung types	[31]
Onthophagus opacicollis	23 July 2014	Wide distribution; associated with sheep and cattle dung; only considered rare in Italy; elsewhere abundant and frequent	[32]

3. Ecology of species

3.1 Longevity

Longevity depends on the species, with a few species living two or more years, but most having a shorter lifespan. Specific information found on the longevity of each of the 14 species is provided in Table 3.

Table 3. Longevity of dung beetle species

Species	Longevity
Geotrupes stercorarius	One- to two-year lifecycle in the UK [33] and France [34]

Species	Longevity
	Two-year life cycle in North America [35 p264]
Ateuchetus laticollis	Potentially up to two years, as most large beetles have lifespans allowing at least two breeding seasons [36 p110]
Cheironitis scabrosus	Unknown for this species; however, *C. furcifer* is univoltine, with a single annual generation [37]
Copris incertus	Female lifespan under laboratory conditions is 580 ± 159 days [38]; hence complete lifecycle will be around 2 years
Copris integer	Unknown for this species, but other *Copris* adults can live for 2 years (see *C. incertus* and *C. lunaris*)
Copris lunaris	Adults survive 2 years [39; 40]
Euoniticellus triangulatus	Unknown
Gymnopleurus humanus	Unknown
Onitis minutus	Unknown
Onthophagus medius	Likely one year, [41]
Onthophagus nuchicornis	One year [42; 43]
Onthophagus opacicollis	Unknown
Scarabaeus sacer	Potentially up to two years, as most large beetles have lifespans allowing at least two breeding seasons [36 p110]
Sisyphus schaefferi	Longevity of 360-400 days [36 p110]

3.2 Weight and length

Lengths range from 5-27 mm and dry weights from 9-671 mg. There are no data available to distinguish males and females on the basis of size. Information found on the size of each of the 14 species is provided in Table 4.

Table 4. Length and weight

Species	Length (mm)	Length References	Weight (mg) dry wt unless specified	Weight References
Geotrupes stercorarius	12–27	[33; 34 p372; 35 p262; 44 p411; 45 p57; 46 p245]	163.5 ± 60.2	[47]
Ateuchetus laticollis	15–25	[34 p26; 44 p381; 45 p319; 46 p52; 48; 49 p8]	172–173 670 ± 140 fresh wt	[44 p411; 48; 50; 51 p36] [52]
Cheironitis scabrosus	Average for the genus is 10.2-16.5	[29 p161]	63	[53]
Copris incertus	12–20	[22; 44 p411; 54]	175	[44 p411]
Copris integer	13–24	[7 p414]	Unknown	
Copris lunaris	15–24	[34 p42; 45 p326; 46 p61; 48; 49 p8]	228 286 ± 50	[48; 49 p8] [55]

Species	Length (mm)	Length References	Weight (mg) dry wt unless specified	Weight References
Euoniticellus triangulatus	7–9	[11 p308; 56]	9	[53]
Gymnopleurus humanus	8.21–10.97	[10]	185 ± 19 fresh wt	[57]
Onitis minutus	8–19	[11 p372; 58; 59]	Unknown	
Onthophagus medius	8–13	[60]	Unknown	
Onthophagus nuchicornis	6–10	[28; 34 p112; 45 p379; 46 p93; 49 p9; 61; 62 p123-124]	22–76	[43]
Onthophagus opacicollis	5–8	[34 p102; 45 p380]	6–22	[47; 51 p113; 55]
Scarabaeus sacer	21–40	[34 p18; 45 p317; 46 p44; 49 p8; 61; 63]	671.2 ± 248.8 2570 ± 540 fresh wt	[51 p40; 55] [52]
Sisyphus schaefferi	6–13	[34 p40; 44 p381; 45 p321; 46; 48; 49 p8; 64-66]	29 10–280 wet wt	[44 p381; 48; 49 p8; 51 p44; 67] [66]

3.3 Identification: description, sexual dimorphism and similar species

The eggs and larvae of Scarabaeinae species generally look similar [e.g., various figures in 68]. Images of the egg (Figure 1) and late instar larva of *Bubas bubalus* (Figure 2) are included as representative examples.

Figure 1. Egg of *Bubas bubalus* in brood ball (photo by Patrick Gleeson, CSIRO)

Figure 2. Late instar larva of *Bubas bubalus* (photos by Patrick Gleeson, CSIRO)

Whilst the pupae of different dung beetle species tend to look different, they also have many similarities [e.g., various figures in 68]. Diagrams of the pupa of female (Figure 3) and male (Figure 4) *Onthophagus andalusicus* are included as examples.

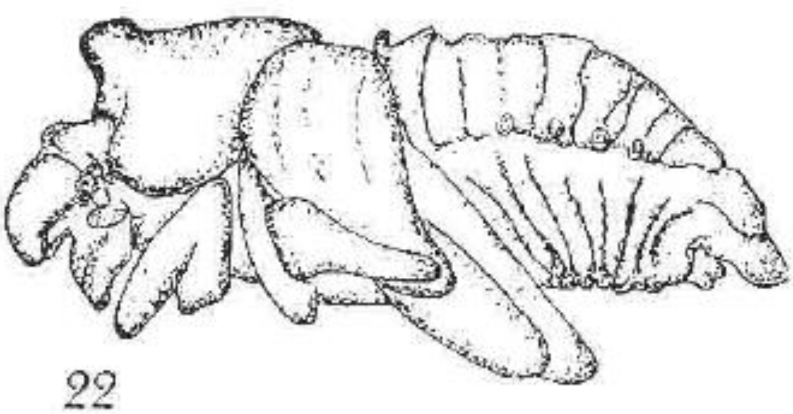


Figure 3: Female pupa of *Onthophagus marginalis* subsp. *andalusicus* [69, used with permission from the authors]

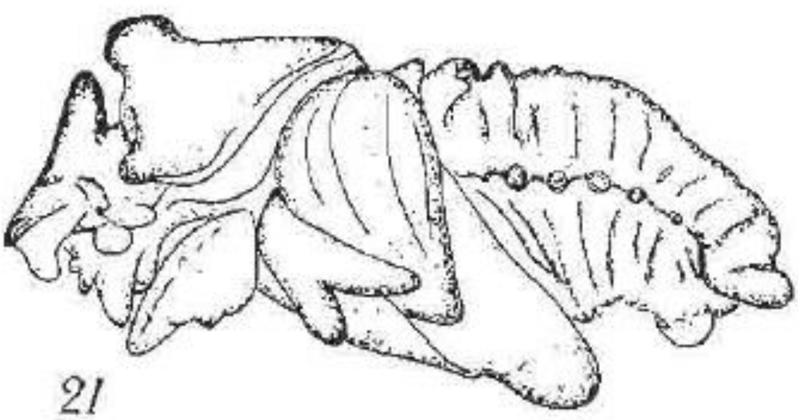


Figure 4: Male pupa of *Onthophagus marginalis* subsp. *andalusicus* [69, used with permission from the authors]

Adults can be identified based on their morphological characteristics. Table 5 summarises information found for each of the 14 species in terms of adult descriptions and sexual dimorphism. Many species have major and minor males. The major males tend to be larger and have well-developed cephalic horns, whilst the minor males tend to be smaller and have either very reduced or absent horns [70 p56]. In the reproductive season, major males tend to combat with other large males, whilst minor males sneak past these competing males to copulate with the female [70 p56].

Table 5. Photos and description of species, with sexual dimorphism noted if applicable or known

Male	**Female**	**Description**	**Sexual Dimorphism**
Geotrupes stercorarius. Photo of male by Udo Schmidt (https://www.flickr.com/photos/coleoptera-us/19372749035/); Creative Commons, freely available; photo of female by Alberto Zampogna, CSIRO Montpellier, France			
		Large elongate beetle with almost parallel-sided elytra; upper surface black with green or blue reflection and often with brighter and more strongly metallic borders to the pronotum and elytra; the underside metallic blue, violet, green or a mixture of these colours and with dense black hairs evenly distributed across the abdomen; abdominal sternites evenly punctured and pubescent throughout; [33]	Male protibia with two ridges on the underside, outer one bearing 1 - 3 large teeth; 3rd outer tooth directed downward; posterior trochanters spiny at apex; metafemurs with a strong tooth at basal third of posterior margin; female legs have no distinctive features [45 p57]
Ateuchetus laticollis. Photos by Alberto Zamprogna, CSIRO Montpellier, France			
		Shiny black beetle; shiny and smooth pronotum with a few large indentations; elytra with lightly engraved stripes [45 p319]	No sexual dimorphic traits
Cheironitis scabrosus. Photos by Christian Deschodt, supplied by Adrian Davis; University of Pretoria, South Africa			

<table>
<tr><th>Male</th><th>Female</th><th>Description</th><th>Sexual Dimorphism</th></tr>
<tr><td></td><td></td><td>Medium beetle, copper head with a bronze shield; short erect horn; thorax with wrinkled hair and a pale green margin; elytra rust-coloured with black dots; black body; legs pale red, black at the apex and base [71 p209]</td><td>For the genus Cheironitis: anterior legs lack tarsi in males but not in females; pronotal disc with raised, transverse sub-anterior ridge distinct in females and unclear in males [29 p161]</td></tr>
<tr><td colspan="4">Copris incertus. Photos of males by Emmy Engasser, Wichita State University, Hawaiian Scarab ID, USDA APHIS PPQ, Bugwood.org. Image numbers 5539215, 553922, 5539716; photo of female from PaDIL (https://www.padil.gov.au/maf-border/pest/main/140404/31192); Creative Commons, freely available. Minor male looks like female.</td></tr>
<tr><td>
Major Male</td><td></td><td rowspan="2">Large beetle; shiny black oval body; elytra have 9 stria, with 8th stria incomplete and never reaching the posterior margin of the elytra [22]</td><td rowspan="2">Cephalic horn is long and well-developed in major males, reduced in minor males, and truncate or missing in females; pronotum of major males has four horn-like protuberances, which are much reduced in minor males and females [22]</td></tr>
<tr><td>
Major Male</td><td>
Minor Male</td></tr>
</table>

Male	Female	Description	Sexual Dimorphism
***Copris integer*.** Photos from http://www.entomoboutique.weonea.com/produit/160206/; Permission to use these was granted by Emmanuel Bonnard, 27 September 2021; photo of female cropped from a photo of a male and female together; photos edited to make background white			
		Large black and shiny beetle; intermediate femurs with numerous apical bristles extending in a long longitudinal row; terminal spur on anterior tibias [7 p414]	Males present significant horns while females have flattened, reduced horns terminating in two distinct teeth [7 p414]
			
Copris lunaris. Photos of males by Udo Schmidt https://www.flickr.com/photos/coleoptera-us/15582233562/in/photostream/; https://www.flickr.com/photos/coleoptera-us/15557710616/in/photostream/); photos of females from UKBeetles [27]; Creative Commons, freely available; lateral photos cropped			
		Large, shiny black beetle; widely expanded anterior margin of the head; pronotum densely and strongly punctured; elytra slightly transverse, each with five striae that continue into the apical third and often to the apex, with broad, weakly convex interstices; legs long and very robust; anterior tibiae with four broad external teeth and a long spur at the internal apical angle; middle and hind tibiae broadly expanded towards the apex, each with a single long sharp spur at the inner apical angle [27]	Males have a long and tapering cephalic horn and the anterior margin of the pronotum produces short lateral horns; females have a short and truncate cephalic horn and the pronotum is simply raised above a flat anterior margin [27]; minor males and females do not have long cephalic horns [72]
			

Male	Female	Description	Sexual Dimorphism
Euoniticellus triangulatus. Photos by Christian Deschodt; supplied by Adrian Davis; University of Pretoria, South Africa			
		Small brown and black elongated beetle; pronotum tightly punctuated with large umbilicated points and many fine points [56 p49, 55]	Male clypeus folded in a V-shape with thickened frontal sections; apex almost reaches the strong and broadly arched frontal carena, followed by a bead usually effaced in its middle; females have an entire frontal keel, with the vertex finely punctuated [56 p49, 55]
Gymnopleurus humanus. Photo by Christian Deschodt; supplied by Adrian Davis; University of Pretoria, South Africa			
		Smallish metallic blue, green or copper coloured beetle; dorsal surface covered with dense, coarse microgranulation; clypeus bidentate; anterior margins of clypeus and genae with dense microgranulation; foreleg with three large, distal, external teeth; sides of abdomen almost parallel, tapering only slightly [10]	Terminal spur on the foreleg has an acute tip in females and a blunt tip in males [10]
Onitis minutus. Photos by Christian Deschodt; supplied by Adrian Davis; University of Pretoria, South Africa			
		Head and pronotum bronze-green; legs and ventral side metallic green; elytra testaceous with greenish sheen; easily recognised by colour, body size, head sculpture of pronotum; legs of male provide good characteristics for distinguishing this species; cephalic surface granulose; clypeal carina almost invisible; pronotum broader than long, somewhat convex, granulose, deep basal impressions; elytra moderately flat, striate, intervals inconspicuously punctuate [59]	Hind legs of males are more sculptured and have a pronounced rectangular terminal spur that is missing in females; terminal spurs on middle legs of males and females are oriented differently; head of female is more triangulate than that of male [59]

Male	**Female**	**Description**	**Sexual Dimorphism**
***Onthophagus medius*.** Photos from UKBeetles [41]; Creative Commons, freely available; lateral photos cropped			
		Medium sized beetle, with contrasting dark forebody and mottled brown elytra; often with a distinct metallic green lustre to the pronotum and head; continuously curved lateral margins to the pronotum; dark variable and random elytral markings do not extend to the base; head with a curved ridge on the vertex, the surface otherwise densely and strongly punctured [41]	Males have a long, curved horn at the base of the head; females have two small side horns but lack the long median horn of the male [41]
			
***Onthophagus nuchicornis*.** Dorsal photos from https://www.coleoptera.org.uk/species/onthophagus-nuchicornis; Creative Commons, freely available; lateral photos by Henri Goulet, Agriculture and Agri-Food Canada, supplied by Kevin Floate, Agriculture and Agri-Food Canada			
		Small to medium sized beetle; head and pronotum black, without a metallic reflection, and finely punctured and pubescent; elytra colouration typically a random series of well-defined dark markings on a pale to dark yellowish-brown ground colour [42]	Males have a single cephalic horn, which can be smaller in minor males; females lack the horn and have a transverse ridge at the base of the head [28; 43]
			

Male	Female	Description	Sexual Dimorphism
Onthophagus opacicollis. https://inpn.mnhn.fr/espece/cd_nom/10859?lg=en; Permission to use these was granted by Patrick Prévost, 28 September 2021			
		Small to medium size beetle; head and pronotum black, more or less tanned or greenish; elytra with abundant irregular and asymmetrical markings; punctuated pronotum, granulated to the base [45 p380]	Males have a single cephalic horn, no frontal carinae; females have a strong, arched frontal carina, but no cephalic horn [45 p380]
			
Scarabaeus sacer. Photo by Udo Schmidt (https://www.flickr.com/photos/coleoptera-us/28486691625/in/photolist); Creative Commons, freely available			
		Large beetle, entirely black; pronotum unevenly punctured with lateral margins strongly rounded and closely denticulate; elytra lightly striate and punctured; front tibia has four strong external teeth and two small teeth [61 p107]	Unknown
Sisyphus schaefferi. Photos by Alberto Zamprogna, CSIRO Montpellier, France			
		Medium sized beetle; entirely black or dark brown elytra may have a metallic lustre; dorsal surface with short, curved, dark setae; v; antennae orange with a dark club; pronotum very convex, with strong micro-sculpture and wide and shallow punctures; elytra strongly tapered towards the apex, with 7 shiny striae with a single row of punctures; fore tibiae well developed, with three large teeth and several smaller ones externally, and a large internal apical spur; hind femur angled internally to form a backward-pointing tooth [65]	Males and females can be distinguished by the shape and size of the metafemoral tubercle [66]

Dung beetle species can look similar to each other: more than half of the species have been flagged as being similar to other species. This information is summarised in Table 6.

Table 6. Similarity to other species

Species	Other species that could be mixed up due to similarity
Geotrupes stercorarius	Similar to *Geotrupes spiniger*: the two species can be separated and identified by the morphology of the pronotum, the abdominal sternites and the hind tibia [33]
Copris incertus	Extremely similar to *Copris remotus*: the two species can be separated by examining the elytra [22] Originally confounded with *Copris amazonicus, Copris brevicornis*, *Copris moroni*, and *Copris susanae*, all of which can now be identified by morphological differences and their discontinuous isolated populations [73]
Copris lunaris	Similar to *Copris hispanus cavolinii* (Petagna, 1792): the two species can be distinguished by the shape of the pronotum [74] Similar to *Typhaeus typhoeus*: can be distinguished by their horns and the anterior margin of the head [42]
Gymnopleurus humanus	Very similar and closely related to *Gymnopleurus humeralis*: the two species can be identified by morphological differences and their different, discontinuous distributions [10]
Onthophagus medius	Very similar to *Onthophagus vacca*: the two species can be identified by a series of morphological traits related to horn shape and position [60; 74]
Onthophagus nuchicornis	Similar to *Onthophagus similis* (Scriba, 1790) in the UK: the two species can be identified by pronotum morphology [42] Similar to *Onthophagus foliaceus* and *Onthophagus granulatus* in Hawaii: males can be distinguished by their horns; females can be identified by pronotum morphology [28]
Onthophagus opacicollis	Similar to *Onthophagus fracticornis*: the two species can be clearly distinguished from one another morphologically [75] and identified by the structure of the clypeus [74]; genetic analysis shows a high degree of difference between *O. fracticornis* and both *O. similis* and *O. opacicollis* [75] Also very similar to *Onthophagus similis*: morphological differences and differences in their distributions (although there are regions of overlap) have been used to separate the species [75; 76]
Scarabaeus sacer	Similar to *Scarabaeus typhon*: the two species can be identified by morphology of the pronotum and frontal suture [61]

3.4 Natural geographic range

The native range of each of the species is summarised in Table 7. This information excludes regions to which species may have been introduced, even if they are now common and well-established in these areas. Information regarding successful introductions to new areas is covered later (Section 5.1). Additional information of factors limiting populations in their natural range is provided below.

Table 7. Natural geographic range of selected species (excluding areas of deliberate introduction)

Species	Natural Geographic range
Geotrupes stercorarius	From Great Britain to Russia [1; 33; 35 p263; 45 p57] Also China and Japan [77]

Species	Natural Geographic range
Ateuchetus laticollis	Northern Africa and Europe: Morocco, Algeria, Spain, Portugal, France, Italy, Corsica, Sardinia [2; 3; 34; 45 p319]
Cheironitis scabrosus	South Africa and Namibia [11 p341]
Copris incertus	Eastern Mexico [73]
Copris integer	East Africa: Burkina Faso [78], Burundi [6; 78], Democratic Republic of Congo [78], Ethiopia [7; 78; 79], Malawi [6], Rwanda [6; 78], Kenya, Tanzania [6; 7; 78-80], Uganda [7; 79] and Zimbabwe [78]
Copris lunaris	All of Europe (except for the northern regions), extending westwards to Iran, Kazakhstan and western Asia [34; 78], into Russia [8] and extending from southern Siberia to China [27]
Euoniticellus triangulatus	East and southern Africa: Kenya [80; 81], Mozambique [82], South Africa [53; 83], Tanzania [9; 80] and Zaire [84] Also Angola, Botswana, Ghana, Lesotho, Malawi and Namibia [9]
Gymnopleurus humanus	Angola, Namibia and South Africa [11 p278]
Onitis minutus	South Africa [11 p372; 13]
Onthophagus medius	Europe; absent from Mediterranean islands; extending eastwards into Turkey, Iran, Kazakhstan and Russia [41; 60]
Onthophagus nuchicornis	Europe; from Portugal to the northern provinces of Fennoscandia; through Asia Minor and Russia to China [28; 34; 42; 61]
Onthophagus opacicollis	Southern Europe, Asia Minor, Syria, Iran and North Africa [34; 74]
Scarabaeus sacer	North Africa, Europe, Asia and Middle East: Afghanistan, Ethiopia, France, Hungary, northern India, Iran, Israel, Kazakhstan, Romania; Palestine, Portugal, Russia and Spain [61] Also Albania, Bulgaria, Greece and Montenegro [85] Also Arabia, Armenia, Corsica, Cyprus, Italy (including Sardinia and Sicily), Syria, Turkey and Yugoslavia [45 p317]
Sisyphus schaefferi	From northern Africa and the Iberian Peninsula to China and Korea [48; 64; 74; 86-88] Does not extend into northern regions, including the UK [65]

3.4.1 Predation

Although there is limited data on predation of dung beetles [89], it is likely to be important [e.g., 37; 90], and substantially underestimated [91]. Predators of dung beetles in general include many kinds of birds, mammals and even reptiles and amphibians [91]. Kingfishers have been recorded aggressively pursuing *S. sacer*, numerous bird species have been recorded eating *G. stercorarius* and *C. lunaris*, and bats and mink have been recorded eating *G. stercorarius* [91]. Overall, the extent of predation as a limiting factor of dung beetle populations is unclear, and further research is recommended [89].

3.4.2 Resource availability

One of the most important population limiting factors for dung beetles is resource (dung) availability [89; 92]. The availability of dung is essential both as a food source for adults and larvae, and for nest construction [e.g., 57; 93]. Adult beetles of some species have been observed on other food sources (Sections 7.1 and 8.3), but as these are not limiting or essential, they are not included as a resource in this section. Preferences for dung type are shown in Section 3.8.1, Table 9.

3.4.3 Competition

Dung beetle species occupying the same niche will compete for both dung and space [94 p37-38]. Roller beetles only compete for dung: competition for space is eliminated as dung balls are moved away from the source [93 p306]. Roller beetles also appear to have an advantage in dung collection over tunnelling beetles, as they do not have to construct their burrow before collecting dung [93 p323]. However, both intra- and inter-specific ball stealing behaviour has been observed in rollers [93 p306-309]. Tunneller beetles compete for both food and for space below the dung pad [94 p37-38].

Nonetheless, a dung pad can host and feed large numbers of dung beetles [70 p54, 65-66; 95 p5; 96 p67-68], with multiple species co-occurring [47; 97-101]. Co-existence can occur because the species of beetles utilise dung differently: feeding and breeding behaviours differ, and patterns of activity differ in terms of flight times (nocturnal, diurnal or crepuscular) and seasonal activity (i.e., when they are most active and breeding) [100]. In general, larval competition for food is largely avoided, as adult beetles provide for each of their offspring, whether they are tunnellers or rollers, and competition for space is avoided by rollers as they relocate dung for feeding or breeding [94 p37]. Interspecific differences in behaviours can also reduce competition. In many temperate dung beetle communities, temporal separation helps account for an apparent lack of competition [e.g., 92]. For example, competition between *A. laticollis* and *S. schaefferi* is decreased by differences in their emergence and breeding periods [50 p114]. In some species, beetles actively avoid the nests of other beetles whilst tunnelling [102]. Flight at different times reduces competition between species, favouring intraspecific rather than interspecific encounters [58], thereby potentially also enhancing mate-finding.

3.4.4 Climate, land use and soil type

Climate necessarily plays a key role in local population dynamics and in determining distributions of beetles [29 p28; 34 p13; 55; 83; 103], as do land use and vegetation [34 p13; 83; 104-106] and soil type [29 p29; 83; 104]. As shown below (Section 3.8.1, Table 9), each species has a preference for particular soil types.

3.5 Migration

Dung beetles are not migratory as such, but will disperse to find dung. For example, *C. incertus* can fly distances in excess of 50 m [23], and *S. schaefferi* can fly upwind for 40-60 m [96 p89-90]. Furthermore, *G. stercorarius* may fly considerable distances from apparently suitable habitats, possibly disoriented by lights [33].

3.6 Ability to hibernate in winter or aestivate in summer

Many species of dung beetle engage in diapause at different times during their life history, as an evolutionary adaptation to tolerate seasonal conditions [50 p109-111; 107 p341], and diapause is sometimes required before breeding can begin [108 p26-50]. Many species have an overwintering period, either as adults or late instar larvae. Overwintering appears to be obligatory for reproduction in *O. nuchicornis* [43; 109]; in other species, it is facultative [40; 41]. Still other species appear capable of reducing activity in inclement weather [23; 55; 65; 81; 110 p17]. The information available on the 14 species is summarised in Table 8.

Table 8. Ability to hibernate, aestivate, and survive adverse conditions

Species	**Overwintering stage**	**Information on hibernation, aestivation and surviving adverse conditions**	**References**
Geotrupes stercorarius	Larva and adult	Third instar larvae overwinter before pupating in summer; adults emerge in fall and overwinter	[33-35]
Ateuchetus laticollis	Adult		[36 p93; 50 p110]
Cheironitis scabrosus	Unknown	Adults only collected during the dry season (April, May and September) in northern South Africa, implying that there is overwintering and/or aestivation and/or decreased activity in other months	[110 p17]
Copris incertus	Larva and adult	Adults emerge in spring in New Zealand, and can cease activity in hot, dry conditions Adults generally emerge in spring from overwintering third instar larvae in New Zealand, and adults emerging in late summer can also overwinter	[23] (SA Forgie, pers. comm.)
Copris integer	N/A	Found year round in Kenya, suggesting there is no aestivation or overwintering	[79 p147]
Copris lunaris	Adult	Adults remain inactive underground in winter, but will feed on days where it is warm enough	[27; 34 p42; 36 p81; 50 p110; 55] [40]
Euoniticellus triangulatus	N/A	Present at all sampling times, suggesting there is no aestivation or overwintering	[53; 81]
Gymnopleurus humanus	Unknown	Adults only active November to April in northern South Africa, implying an overwintering or inactive period	[110 p9]
Onitis minutus	Unknown	Autumn-active species therefore likely to have some kind of developmental pause in its lifecycle	[58 p449]
Onthophagus medius	Adults	Adults overwinter in the soil	[60 p27; 111]
Onthophagus nuchicornis	Adult	Obligatory winter diapause of adults required for reproduction	[43; 109]
Onthophagus opacicollis	Unknown	Adults trapped throughout the year in western Spain (Salamanca), but with much lower numbers in winter No adults trapped in autumn or winter in southwest Spain (Olivenza) Adults have reduced activity in dry period of summer in France	[55] [112] [34]
Scarabaeus sacer	Adult	No adults trapped in winter	[34 p18; 55; 85; 113]

Species	Overwintering stage	Information on hibernation, aestivation and surviving adverse conditions	References
Sisyphus schaefferi	Adult	Adults overwinter	[34, p40; 48 p578-9; 49, p35; 66]
		Adults may shelter under logs or among litter during bad weather	[65]

3.7 Breathing atmospheric air

Being land animals, dung beetles necessarily breathe atmospheric air.

3.8 Habitat requirements

Dung beetles have defined habitat preferences, whether this be for open pastures or forests, specific soil, dung types or climate. Table 9 details the habitat requirements for each of the 14 species listed.

3.8.1 Physical parameters

Information on the physical traits (soil type and dung used) of the natural habitat is summarised in Table 9.

Table 9. Physical parameters of natural habitat important to dung beetles

Species	Habitat	Soil Type	Dung Used
Geotrupes stercorarius	Pasture [20; 34 p372; 47] Forest/woodland [20; 34 p372]	Varied soil types, but often heavy and clay rich [34 p372]	cow [33; 34 p372; 35 p263; 86] sheep [47] horse [33; 34 p372; 35 p263] human, goat, fox and deer [34 p372]
Ateuchetus laticollis	Pasture and light woodland [34 p26; 49; 51 p36-37]	Little preference for soil type [3; 34 p26; 36 p92; 49 p23; 50 p105]	cow [34 p26; 48; 105], sheep [34 p26; 105] horse [3; 34 p26] human [34 p26; 96 p17] dog [34 p26]
Cheironitis scabrosus	Grassland and shrubland [11 p341; 30; 53; 83] Crop fields [11 p341]	Primarily sand [83; 98]	cow [11 p341; 30; 53; 98; 110; 114] sheep, horse [11 p341; 98] goat, gemsbok, blesbok and springbok [98]
Copris incertus	Pasture [115]	Volcanic and clay soils [23] Clays and loams [24]	cow, sheep, horse [23; 24] alpaca [24] human and pig [73]
Copris integer	Savanna [79]	Sandy to clay soils [79; 80]	generalist [79]
Copris lunaris	Open pasture, woodland, moor and heathland [27; 55]	Deep, humid soils [36 p80] Sandy clay [49] Sandy or chalky soils [27]	cow [34 p42; 36 p80; 40; 48; 55; 74; 86] sheep [34 p42; 49] horse [27]
Euoniticellus triangulatus	Grassland [11 p308; 53; 81; 84] Only rarely in wetland [81]	Sandy soils [11 p308; 53; 80; 81; 83] Clay soils [11 p308; 80]	cow [11 p308; 53; 81] horse and buffalo [11 p308]
Gymnopleurus humanus	Grassland and shrubland [11 p278; 31; 110]	Primarily sandy type soils [31; 98] Deep stony soils [97]	wide range of dung types [31] cow, sheep, horse, donkey, zebra, baboon [11 p278] pig [11 p278; 97]
Onitis minutus	Grassland, scrub, shrubland, pasture and fallow crop fields [11 p372]	Mostly sandy loam with few records on sand, sandy clay and clay [11 p372; 83]	cow [11 p372]
Onthophagus medius	Pasture and meadow [74]	Sandy soils [74; 111]	cow, sheep, horse [41; 74]

Species	Habitat	Soil Type	Dung Used
	Floodplains [41]	Alluvial soils [41]	donkey [74]
Onthophagus nuchicornis	Rangeland and grassland [42; 43; 109; 116] Coastal dunes and open areas [34; 42]	Sandy soils [34; 42; 49]	generalist [43] cow [34 p112; 62 p126; 109] sheep [34 p112; 49] horse [34 p112; 62 p126] human [34 p112]
Onthophagus opacicollis	Grassland/pasture [34 p102; 47; 51 p114; 74] Shrubland/woodland [34 p102; 51 p114; 105; 117] wetlands [105; 117]	Limestone sediments [74] Light to heavy soils [34; 61 p43; 118]	cow [34 p102; 55; 105; 117] sheep [34 p102; 105] horse [34 p102; 117; 118] human, wild boar [34 p102; 117] dog [34 p102] fallow deer [117]
Scarabaeus sacer	Exclusively in open environments [51 p41], including lawns, dune ridges and river banks [34 p18; 61 p108] Shrubland and marsh [117]	Light sandy clay and silty sands [34 p18; 36 p92; 49; 50 p105; 113; 117]	diverse [113] cow [34 p18; 49; 55; 63] sheep [34 p18; 49] horse [63; 117] dog [113] human [34 p18; 96 p17] deer [63]
Sisyphus schaefferi	Pasture and light woodland [34 p40; 49; 51 p45; 64]	Mostly on clay soils [34 p40; 49 p23; 50 p105; 64]	cow [34 p40; 64; 65; 67; 74; 86; 119] sheep [34 p40; 49; 65; 74; 119] goat [64; 67; 86] horse [34 p40; 64; 74] human [34 p40; 119] fox, badger [34 p40] red deer, wild boar [64] deer [65]

3.8.2 Climatic preferences

Information on the climatic traits of the natural habitat is summarised in Table 10. If known, this also includes any specific temperature requirements for activity.

Table 10. Climatic requirements within natural habitat

Species	Climate/Temperature	Seasonality/Activity
Geotrupes stercorarius	Requires sufficiently high annual rainfall and low annual average temperatures [34 p372] Snowy winters and mild summers [47]	Spring to autumn [50 p110]
Ateuchetus laticollis	Mediterranean climate [3; 34 p26; 48; 49; 50 p107; 105]	February to November, with reduced activity in August (dry) [34 p26] Primarily autumn; minor activity in spring in Morocco [51 p36-37] Activity (ball-rolling implied) occurs between 22-30 °C, [96 p64]
Cheironitis scabrosus	Mediterranean climate [120] Found in areas of winter, bimodal and late summer rainfall [83] Arid ecoregions [30; 98] Annual rainfall to 510 mm, annual mean temperature between 11-21 ˚C [11 p341; 30]	Dry season [53] Spring to autumn (Sept-Apr), but primarily in summer (rainy or dry) [11 p341]
Copris incertus	Native distribution is in tropical (equatorial) climates, based on Köppen-Geiger climate classification [121; 122] temperate wet areas (e.g., New Zealand) [23; 24]	Associated with high rainfall; able to cease activity in hot, dry conditions [23] Spring to early summer and late summer to autumn in New Zealand; in mild winters will breed in July (SA Forgie, pers. comm.)
Copris integer	Semi-arid climate [79] Annual rainfall to 2 000 mm [80]	Found year round in Kenya [79 p147]
Copris lunaris	Mediterranean to temperate climate [27; 48; 50 Table 6.5; 55; 72; 74] Moderate climate, with average temperature of 8 ˚C in winter and 25 ˚C in summer [123]	Spring, with a little activity in summer [55] Summer [48; 50 p110]
Euoniticellus triangulatus	Found in areas of winter, bimodal, and midsummer (highveld to northeast subtropical and tropical) rainfall [83] Annual rainfall < 1 200 mm, annual mean temperature between 4-25 ˚C [11 p308; 81]	Found year round [53; 81] Greatest abundance from late spring to early autumn [11 p308]
Gymnopleurus humanus	Annual rainfall < 800 mm [10; 31; 97] Annual mean temperature between 11-23 ˚C [11 p278; 31]	Late summer rainy season [11 p278]
Onitis minutus	Annual rainfall < 500 mm, annual mean temperature between 14-20 ˚C [11 p372]	October, May and June [11 p372]

Species	Climate/Temperature	Seasonality/Activity
Onthophagus medius	Mediterranean climate [74] Humid and temperate climate [41; 60]	Peak in May, short activity period in summer [60] April to autumn, with peaks in May and September [41]
Onthophagus nuchicornis	Temperate [28; 62] Cold temperate regions [116] Egg to adult development occurs between 16-30 ˚C [109]	April to September, with spring and autumn peaks [42]
Onthophagus opacicollis	Mediterranean climate [55; 74; 105]	Primarily in spring and autumn, reduced activity in summer and winter [55] Decreased activity in driest periods of summer [34 p102]
Scarabaeus sacer	Mediterranean climate [55; 63; 113; 117] Annual rainfall between 200-800 mm [63]	Spring to autumn, depending on the country and its climate [34 p18; 51 p41; 55; 63; 85; 113; 117] Activity (ball-rolling implied) occurs between 22-30 °C [96 p64]
Sisyphus schaefferi	Mediterranean climate [48; 49; 65; 74]	Spring to autumn [34 p40; 48; 51 p45; 64; 66; 87] Ball-rolling begins at 20 °C, peaking between 25-30°C [96 p64]

3.8.3 Use of nest sites

Dung beetles do not use nests as a specific area where individuals return to in order to sleep, bear or rear young. However, the term nest is used to define a cluster of brood balls buried in the soil.

3.8.4 Use of marshes or swamps, estuaries, lakes, ponds or dams, rivers, channels or streams, banks of water bodies, coastal beaches or sand dunes

Dung beetles are primarily found in pastures, savannahs, shrublands, sometimes in forests and crops (see Table 9). A few species may occasionally venture in wetlands (*Euoniticellus triangulatus* [81]) or alongside streams (*Onthophagus opacicollis* [117]). They are unlikely to have a negative impact on these habitats: if anything, they help prevent runoff of excessive nutrients that could lead to eutrophication of these habitats [70 p23; 124].

3.9 Social behaviour and groupings

Dung beetles can occur in groups when feeding on or collecting dung from dung pads for reproduction [70; 93], and large numbers may be found on a single pad [70 p54, 65-66; 95 p5]. In some species, male and female dung beetles will cooperate with one another when breeding or nesting [68]. For example, male-female pairs of *Copris* beetles will work together to transport the dung into the breeding chambers [39; 68 p93-102; 90], and *S. sacer* couples engage in a complex ritual of ball rolling before mating [125]. However, once mated, it may only be the female that forms and buries the brood balls, as in *S. sacer* [125], or both males and females may cooperate in building and provisioning the nest, as in *S. schaefferi* [65].

3.10 Territorial and aggressive behaviour

Dung beetles are not generally aggressive animals, although aggression towards conspecifics may occur during the breeding season. For example, fights are common when *S. sacer* couples engage in ball rolling before mating, [125], and in *S. schaefferi*, successive combats when rolling a ball of dung can last up to 32 minutes [66]. Whilst combat in beetles may widely occur, it is perceived as form of sexual behaviour, with dung being the object of contention, not another individual [96 p162-165].

3.11 Characteristics that may cause harm to humans or any other species

Dung beetles do not pose a bite or injury risk to other animals or humans due to the nature of their mouthparts, which are designed for sucking up liquids and grinding nutritious particles in the dung [126]. Because they are only associated with dung, they do not pose a risk to humans or to native fauna, and they are unlikely to become pests.

4. Reproductive biology

Dung beetles are primarily found in pastures, savannahs, shrublands, sometimes in forests and crops (Table 9), and as such, produce nests on or under the ground of their environment. Details on nest characteristics for each species is summarised in Table 11.

There are four categories of dung beetles: dwellers (endocoprids), tunnellers (paracoprids), rollers (telecoprids) and kleptoparasites (kleptocoprids) [57; 94; 100]. Dwellers spend their entire life cycle in the dung, or possibly part of the lifecycle just under the surface of the soil, and kleptoparasites utilise dung stores of other species [57; 94; 100]. Therefore, these two categories are not considered in this application. Apart from four roller species (*A. laticollis*, *G. humanus, S. sacer* and *S. schaefferi*), all other species in this application are tunnellers (Table 11).

Rollers remove portions of the dung, roll it into a ball, and bury it superficially in the soil or place it in vegetation tussocks some distance away from the dung [57; 94; 100; 127]. Males, females or both may contribute to ball rolling, digging and making the brood chambers [65; 94], and some species also make and roll balls for feeding [57; 94].

Tunnellers burrow into the soil directly underneath or very close to the dung pad. Nest architecture and depth of tunnels vary between species, with a primary tunnel that may branch into secondary tunnels where dung balls or sausages are placed (Table 11). Larger species, such as *G. stercorarius*, can dig tunnels down to 50 cm [33; 127], whilst smaller ones, such as *O. nuchicornis*, only dig tunnels 5-15 cm deep [109]. *Cheironitis* species make a simple or branched tunnel [68 p76], whilst *Copris* species have an enlarged nesting chamber at the end of the main tunnel [36 p81-88; 90].

Table 11. Beetle type and notes on oviposition sites and behaviour

Species	Dung Beetle Category	Nest Location / Other Notes
Geotrupes stercorarius	Tunneller [33; 127]	Both sexes dig the tunnel, and the female then digs a series of horizontal brood chambers (galleries), provisioning each with dung and an egg [33]
Ateuchetus laticollis	Roller [48; 49; 52]	Female may produce two brood balls from a single dung ball [36 p106; 125]
Cheironitis scabrosus	Tunneller [98 p82]	

Species	Dung Beetle Category	Nest Location / Other Notes
Copris incertus	Tunneller [44 p411]	Female tunnels 15-35cm deep into the soil, under or near dung pad; mating occurs during excavation; males and females fill the chamber with dung; female seals chamber and makes an average of 5 brood balls with an egg in each, and guards this compound nest from fungi and predators throughout development, only leaving nest just before or when new adults emerge [90] Female lays up to 10 eggs per nest (usually 3-7) [38]
Copris integer	*Copris* species are tunnellers [39; 50]	
Copris lunaris	Tunneller [50 p102; 128]	Female digs oblique tunnel 10-15 cm deep directly below dung; after feeding period, males arrive and couple with females and continue to feed; both sexes build an enlarged brood chamber slightly deeper (to 30 cm) and cooperate to fill brood chamber with dung from the pad above; about a week later the female eventually makes up to 9 brood balls with an egg in each, depending on the amount of dung available; female cares for nest for 4 months [36 p81-88] or until new adults emerge [27; 40]
Euoniticellus triangulatus	Tunneller [81]	*Euoniticellus* species have compound nests, directly below dung, with single brood ovoids in the branched tips of the tunnel [29 p25, 236]
Gymnopleurus humanus	Roller [57]	
Onitis minutus	Tunneller [29 p172]	*Onitis* species have single tunnels with branched tips; brood ovoids (containing an egg) may be single or clustered together in the branched tips; dung sausages (containing 2 or more eggs laid at intervals in the sausage) may be present in the main tunnel or in the terminal branches; dung burial is often delayed for a number of days [29 p172]
Onthophagus medius	Tunneller [41]	Adults excavate burrows directly below dung; female uses dung to provision brood masses [41]
Onthophagus nuchicornis	Tunneller [28; 43; 116]	Adults burrow beneath or near dung pad; burrows have multiple branches forming brood-chambers; each is provisioned with dung into which a single egg is laid [42; 43; 116] 8-18 brood balls buried per beetle [43] Nests are 5-15 cm deep [109]
Onthophagus opacicollis	Tunneller [47]	
Scarabaeus sacer	Roller [52; 129]	Horizontal tunnel 9-10 cm long ends in an enlarged egg chamber; when brood ball (pear) is complete with an egg inside, female abandons nest; one brood ball per nest [36 p104-108] If there is strong competition (lots of beetles), beetles may roll smaller balls or fragments of dung; food balls may be rolled individually, but commonly as a pair; mating occurs on surface or after burying dung ball; generally male buries ball, then leaves female to search for another mate; female remains with ball until it is eaten; after feeding, female rolls

Species	Dung Beetle Category	Nest Location / Other Notes
		nesting (brood) balls and buries them; each buried ball is transformed into an egg chamber; one brood ball per nest [125] Depth of tunnel depends on soil type: nests in central Asia nesting are 40 cm deep in loose soil and 7-20 cm in more compact or stony soil [96]
Sisyphus schaefferi	Roller [64]	Burrow dug into the soil with horizontal chamber 2-3 cm long ending in an enlarged egg chamber; once brood ball (pear) is complete with an egg inside, female abandons nest [36 p104-108] Brood burrows generally initiated by males; completed by both males and females; fresh dung rolled into burrow by both sexes; female takes it in whilst male guards tunnel; female inserts single egg into the ball; leaves the burrow; both sexes seal tunnel, fly off and start process again [65]

4.1 Sexual maturity, triggers for breeding and frequency of breeding

In general, dung beetles need a feeding phase after emergence from the brood chamber in order to allow gonads to mature [70]. This period of adult feeding is generally lengthy [96 p87-88]. It seems that once this feeding and gonad maturation phase is complete, reproductive behaviour occurs, and sexual encounters occur by accidental contact, with the search for a mate being inextricably linked to the search for food [96 p155-156]. For ball-rolling to occur, the ambient temperature must be suitable, and certain olfactory and tactile stimuli are required [96 p103]. During the breeding season, dung beetles produce multiple offspring, although the numbers of eggs and nests vary per species (Table 12). Information found for each species on the the age at sexual maturity, triggers for breeding and the frequency of breeding is provided in Table 12.

Table 12. Age of sexual maturity, triggers for and frequency of breeding

Species	**Age of Sexual Maturity / Triggers for Breeding**	**Frequency of Breeding**
Geotrupes stercorarius	Mating occurs after overwintering [33-35]	3-6 eggs/nest [Spaney 1910 in 127 p206] As females can lay 4-17 eggs [127 p206], females likely to repeat the nesting cycle in a season
Ateuchetus laticollis	Approximately 6 months for gonad maturation phase [36 p95-96] 3-4 weeks feeding and maturation period when beetles emerge in spring [125] Temperature must be between 22-30 °C [96 p64]	Multiple ovipositions in a season [48; 125; 130 p25]
Cheironitis scabrosus	Unknown	Unknown, but *Cheironitis* species have repeated nesting in a season [68 p36-37, 65, 76]
Copris incertus	Copulation occurs 10-40 days after emergence [38; 131]	1-4 nesting cycles per year [38]
Copris integer	Unknown	Unknown. Some *Copris* species build a single nest, others build more [68 p38, 92-102]
Copris lunaris	Mating occurs shortly after emergence in autumn; nesting occurs the following spring after feeding for 3-4 weeks [40] Overwintering adults emerge in May, and have a period of feeding before mating [27] Virgin females mated in spring begin nesting withing a few hours [40]	One nest per year, containing 4-7 brood balls; may reproduce for 2 years [39; 40]
Euoniticellus triangulatus	Unknown; however, *E. intermedius* begins oviposition within 5 days of emergence [68 p69]	Repeated nesting in a season, each with multiple ovipositions [29 p25, 236; 68 p69]
Gymnopleurus humanus	Unknown	Unknown, but will have repeated nesting in a season [68 p39]
Onitis minutus	Unknown	Unknown, but *Onitis* species have multiple nests in a season [68 p36, 65, 70-76]
Onthophagus medius	New generation adults emerge in late summer; overwinter or feed on surface until spring, when breeding occurs [41], implying that there is a maturation period before breeding commences, and there may be a temperature and/or daylength trigger for breeding	Unknown. Likely to be repeated nesting in a season with compound nests [68; 132]
Onthophagus nuchicornis	Mating occurs in spring [42], after adults have overwintered [42; 43;	Repeated nesting in a season, each with multiple ovipositions [43; 68 p36, 78]

Species	Age of Sexual Maturity / Triggers for Breeding	Frequency of Breeding
	109]; hence several months to reach sexual maturity Overwintering diapause is required for reproduction [109]	
Onthophagus opacicollis	Breeding only happens in spring [34 p102] despite year round activity [34 p102; 55], implying a temperature and/or daylength trigger for breeding	Single or compound nests with multiple nests in a season [68 p36, 76-78]
Scarabaeus sacer	After emerging in spring, both sexes have a 3-4 week feeding period allowing females to reach sexual maturity [125] Mating occurs when males and females cooperate to bury dung for feeding and maturation [125] Ball rolling serves as a sexual attractant [68 p82] and brood ball formation begins immediately after copulation [68 p132] Temperature must be between 22-30 °C [96 p64]	Simple nest with repeated nesting in a season [68 p39, 132]
Sisyphus schaefferi	Adults emerge in summer, overwinter, then have a feeding and maturation period in spring before breeding [65]; therefore 6+ months to sexual maturity Females copulate before each nesting sequence [94 p43] Mating occurs in spring, needs a minimum air temperature of 18 °C [36 p98] Partnered collaboration in rolling and burying of dung is necessary for nesting [66] Ball-rolling begins at 20 °C, peaking between 25-30 °C [96 p64]	Simple nest with repeated nesting in a season [68 p39-40] Female can make up to 12 brood balls in a season [36 p109-110; 65]

4.2 Development period

The time taken for full development from egg to adult in many species is unknown, although it is likely to be temperature-dependent. Development time varies between species, and may even vary within a species, as occurs in *G. stercorarius*, where some larvae pupate and produce adults in the autumn, whilst others overwinter and pupate the following spring [33]. Known development times are provided in Table 13.

Table 13. Development period

Species	Development period
Geotrupes stercorarius	170 days (approximately 5.5 months) to reach third instar [36, p57] Either 6 months or 12 months [calculated from 33] 16-17 months [calculated from 35 p263-264] Development from egg to adult takes 242 days (about 8 months) at 16-20 ˚C [133]
Ateuchetus laticollis	Development from egg to adult takes about 6 months: breeding occurs in spring [36 p95-96; 125]; adults eclose after autumn rains have softened the brood ball [36 p108] Development period of 5 months [50 p110]
Cheironitis scabrosus	Unknown
Copris incertus	Development from egg to adult takes 57-70 days at 24±2 °C [134] Development from egg to adult takes 8-12 weeks (2-3 months) depending on soil temperature [135] Care of brood balls lasts 88±16 days (about 3 months) [115]
Copris integer	Unknown
Copris lunaris	About 90 days (3 months) from egg to adult at 20°C [34 p42] About 4 months from egg to adult [36 p88]
Euoniticellus triangulatus	Unknown for this species. Likely to be relatively quick: development from egg to adult in *Euoniticellus intermedius* takes 5-6 weeks [136]
Gymnopleurus humanus	Unknown
Onitis minutus	Unknown
Onthophagus medius	Development from egg to adult takes 3-5 months [calculated from 41]
Onthophagus nuchicornis	Development from egg to adult takes 3-5 months [calculated from 42] Development is temperature dependent: about 1 month at 30 ˚C and almost 4 months at 16 ˚C [109]
Onthophagus opacicollis	Unknown
Scarabaeus sacer	Unknown
Sisyphus schaefferi	Development from egg to adult takes 3-5 months [calculated from 65] Development from egg to adult takes 4-5 months [calculated from 66] 5 months [50 p111] Development from egg to adult takes 41-49 days [Prasse 1957c in 96 p178-179]

4.3 Ability to hybridise

Hybridisation has only been shown to occur in sibling species of *Onthophagus* beetles. Different authors perceive *O. opacicollis* and *O. similis* as either two sibling species with a wide range of sympatry, or as two morphotypes of a single polymorphic species [76; 137]. In Spain, populations do not interbreed in some areas, but do in others, suggesting that speciation is not complete [76]; however, chromosomal analysis indicates no exchange of chromosomes, suggesting that hybridisation does not occur where the species co-occur [137]. If we consider hybridisation by *O. opacicollis* to still be unresolved, it is nonetheless clear from these two studies that this species only potentially hybridises with *O. similis*, and not even with the next closest species, *O. fracticornis* [76;

137]. As such, it is highly unlikely that *O. opacicollis* will hybridise with another species of dung beetle in Australia, whether it be native or introduced. In general, different species of dung beetles do not breed hybrids due to variance in their genital shape and size: they must have compatible genitals to mate with each other [e.g., see 138].

Although *O. vacca* and *O. medius* were originally identified as two different species by Erichson in 1848 [e.g., see 60], variation in external morphology caused them to be generally treated as a single species [60; 139]. The two species have overlapping distributions [60; 74; 140]. They were finally re-distinguished as different species, based on morphological characteristics [60], and DNA analyses supports the fact that they are two separate species [111; 140] that diverged at least 5 million years ago [140]. Nonetheless, it also appears that whilst a small number of F1 hybrids have been reared in the laboratory, no hybrids have been collected in the field, suggesting that the two species are reproductively isolated [111; 140]. Although *O. vacca* and *O. medius* are commonly found at the same place and at the same time [139; 141], phenological asynchrony also occurs, with *O. vacca* adults generally emerging about two months earlier than *O. medius* adults, both in the laboratory and the field [111]. Hence, whilst it is theoretically possible for hybridisation between *O. vacca* and *O. medius* to occur in the field, it has never been shown to occur and is unlikely to be significant in Australia.

4.4 Are individuals single sexed or hermaphroditic?

Dung beetles are either male or female [45 p11-12, 14], and there is no scientific evidence that dung beetles can change sex during their life.

5. Feral populations

5.1 Established breeding population outside native range

Three of the species included in this application have already been successfully introduced elsewhere. It is not clear whether introductions of *G. stercorarius* were deliberate or accidental, but it now occurs in several places (New Brunswick, Prince Edward Island and Quebec) in Canada [34 p372; 35 p265]. *Copris incertus* has been intentionally and successfully released in numerous countries: Hawaii [22], New Zealand [23; 24; 54; 73; 135], Fiji, New Caledonia, Solomon Islands and Vanuatu [54; 73]. In New Zealand, *C. incertus* is part of a current dung beetle release program to improve soils and rehabilitate waterways [124]. *Onthophagus nuchicornis* was apparently accidentally introduced into North America [42], and it is now well-established across the northern United States of America and southern Canada [42; 142].

5.2 Pest status

None of the species on this application are considered as pests anywhere: as with other introduced dung beetles, the three species that have been introduced elsewhere are all considered to be of benefit in their new environments, by removing dung, reducing negative impacts of other pests, and by improving soil health [e..g., 22; 24; 143]. In addition, imported dung beetles, including *C. incertus*, are considered to be cost-effective, sustainable, non-invasive, and have been approved by the government and the Environmental Protection Agency in New Zealand [124]. For similar reasons, 44 species of dung beetle have been imported and 23 have successfully established in Australia [70 p50; 144 p6], and additional species have been released or are being evaluated [145]. There is no information available to suggest that any of these species are being managed in any way to reduce population numbers. As mentioned above (Section 5.1), New Zealand has an active, ongoing program of releasing *C. incertus*, along with other introduced dung beetles [124].

5.3 Other introductions

Five species on this application have been introduced to new environments but failed to establish. *Onthophagus nuchicornis* was introduced to Hawaii in 1910 to help control the horn fly, but failed to establish [28; 42]. Failure to establish in Hawaii may be due to the fact that this species has an obligatory overwintering diapause period as a requirement for reproduction [109], and this may not be possible in Hawaii.

Cheironitis sp. nr *scabrosus* was introduced in a single release (October 1972) to a single location in New South Wales in 1972 [144 p38]. Failure to establish may have been due to the low number (400) of beetles released.

Copris incertus was released in Guam in 1953 but failed to establish [22]. It is not clear why this introduction failed, as *C. incertus* has successfully been introduced to Hawaii [22]. Insectary-bred beetles from Hawaii were also introduced to northern parts of Australia in 1968 – 1971 [54], and 2 937 beetles from Mexico were released at 20 sites across northern Australia (1969 – 1978), but all failed to establish [144 p6, 39]. Again, failure to establish may have been due to the low numbers of beetles released at the sites: the maximum number of *C. incertus* introduced at any site was 399 [144 p39]. However, it is also possible that *C. incertus* may have failed to establish in northern Australia because of an insufficient volume of high-quality dung available at the release sites when the beetles were released, since a release of only 100 *C. incertus* (50 males and 50 females) resulted in a population explosion northwest of Auckland, New Zealand (SA Forgie, pers. comm.). Some of these releases may also have been made in areas climatically marginal for this species (Section 7.2, Table 14).

Copris lunaris was introduced from Italy and France to a single site in New South Wales (near Uriarra Forest) over a thirteen-month period (December 1982 – January 1984), but failed to establish [144 p2, 39]. However, over that thirteen-month time frame, only 96 beetles were introduced, so it is likely that too few beetles were introduced at any point in time to enable establishment.

Onthophagus opacicollis was introduced from Greece to three sites in southwest Western Australia (April – June 1982) but failed to establish [144 p41]. Although 2 100 beetles were introduced, with all sites receiving at least 500 beetles, and 1 000 beetles released at a single site (near Moora) [144 p41], the introductions were spread over three months [144 p2]. Since it is not clear how many beetles were released at each occasion, it is possible that each release contained an insufficient number of beetles to enable successful establishment.

6. Environmental risk assessments of the species

We have not found any reports of risk assessments done on any of the species in this application. Four species were found on the IUCN Red List of Threatened Species, all ranked as of Least Concern (Section 2). Both *A. laticollis* and *O. opacicollis* are not considered to be threatened due to their wide distributions, locally abundant subpopulations, and their occurrence in several protected areas [3; 32]. *Cheironitis scabrosus* is not considered threatened as it is widely distributed in southwest South Africa, commonly occurs in cattle dung, and cattle farming is common throughout its range [30].

Gymnopleurus humanus is adaptable, widely spread, a dominant member of beetle assemblages within its range, and utilises a wide range of dung; therefore, it is not considered to be threatened [31].

Introduced dung beetles are considered beneficial in Australia, with 23 introduced species established to date [70; 144], reducing the density of pest flies, improving pasture quality and soil structure, and potentially reducing eutrophication of waterways [70]. The species were selected to fill spatial and temporal gaps identified by examining current dung beetle distributions in conjunction with data on the distribution of sheep and cattle in Australia. Because dung beetles only feed on dung, and the species selected have strong preference for cattle and sheep dung, they are not expected to pose a risk to humans or to native flora or fauna, and they are unlikely to become pests. They are also unlikely to compete with native beetles for resources.

Most recently, CSIRO successfully applied to have *Bubas bubalus*, *Euonthophagus crocatus*, *Gymnopleurus sturmi*, *Onthophagus vacca* and *Onthophagus marginalis* subsp. *andalusicus* added to the Live Import List, and obtained an importation permit from Department of Agriculture, Water and the Environment for all species. *Bubas bubalus* and *O. vacca* have been released following their importation but are yet to have officially established. *Gymnopleurus sturmi* and *O. m. andalusicus*, have been imported more recently but have not yet been released. Import risks are mitigated by keeping imported adult beetles in an Approved Arrangements facility and sterilising their eggs in Virkon® before removing them from quarantine.

Formal Import Risk Analyses have not been undertaken specifically for any of the species in this application. A permit issued by the Department of Agriculture, Water and the Environment will be required to import these species.

7. Likelihood of establishment in Australia

The aim of importing these species is to release them to establish breeding populations in Australia and fill the current seasonal and geographical gaps in dung beetle activity, so as to better control dung. The following points outline the information required for determining the likelihood that the species could successfully establish in Australia.

7.1 Ability to find food sources

Dung beetles use odour (chemoreception) to locate dung. They either actively fly around and search for dung, or sit and wait for odour trails to reach them and lead them to dung, and once located, the dung is approached by flight [94 p40-42; 96 p88-89]. Exotic dung beetles introduced to Australia seem to disperse depending on where livestock dung is found. For example, introduced *Bubas bison* were found to remain in the original cattle pasture in areas of permanent stocking, only moving between pads a few metres away, whereas in a different area, a colony of the same species was found to leave the original paddock to follow cattle being moved to paddocks up to a kilometre away [70 p60]. Some beetles previously introduced into Australia have spread at a rate of 50-80 kilometres per year (*Digitonthophagus gazella* and *Euoniticellus intermedius*), whilst others have only spread one half to four kilometres per year (*Bubas bison*, *Onitis caffer* and *Geotrupes spiniger*) due to limited flight activity [70 p59]. *Copris incertus* has been recorded to have spread at a rate of 20 km in 20 years in New Zealand (SA Forgie, pers. comm.), and can fly distances in excess of 50 m [23], whilst *Sisyphus schaefferi* can fly upwind for 40-60 m [96 p89-90].

Dung beetles in this application all feed on dung from cattle, sheep and horses, although they may have a wider range (i.e., human, dog, alpaca, etc., see Section 3.8.1, Table 9). As such, they should not compete with native species for food, as native species generally have different dung preferences [70 p74]. Although some native species utilise cattle and horse dung, these species are not considered to be at risk since increased dung availability from increased livestock production is thought to have increased their population numbers [70 p74].

Adult beetles of some species have occasionally been recorded using other food sources: *G. stercorarius* [20; 33], *O. nuchicornis* [42], and *S. schaefferi* [119] have been reported from fungi, *O. nuchicornis* has been reported on decaying plant material [42], and *G. humanus* [110 p9], *O. nuchicornis* [42; 146], *S. sacer* [63; Fausek 1906 in 96 p18, Paulian 1938 in 96, p33] and *S. schaefferi* [Paulian 1938 and Panin 1937 in 96 p33] have all been found on carrion. However, these are generally not the primary food sources for coprophagous beetles [96 p33-34], and feeding on these sources do not pose a risk to either livestock or to commercial plants (see Section 8.3).

7.2 Ability to survive and adapt to climatic conditions

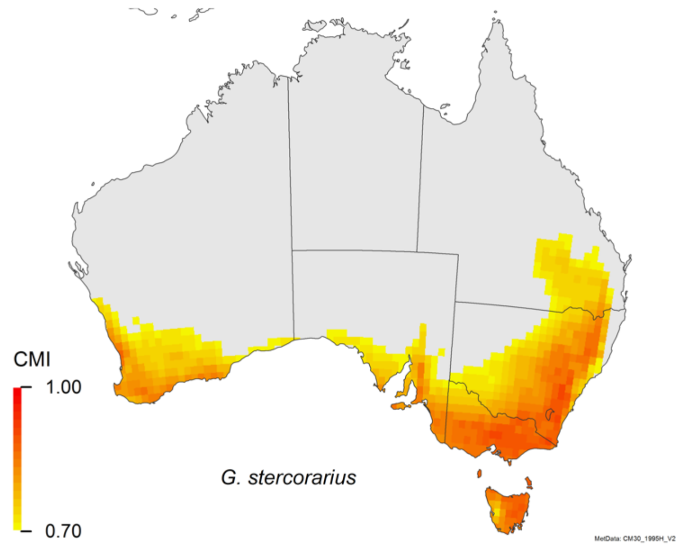
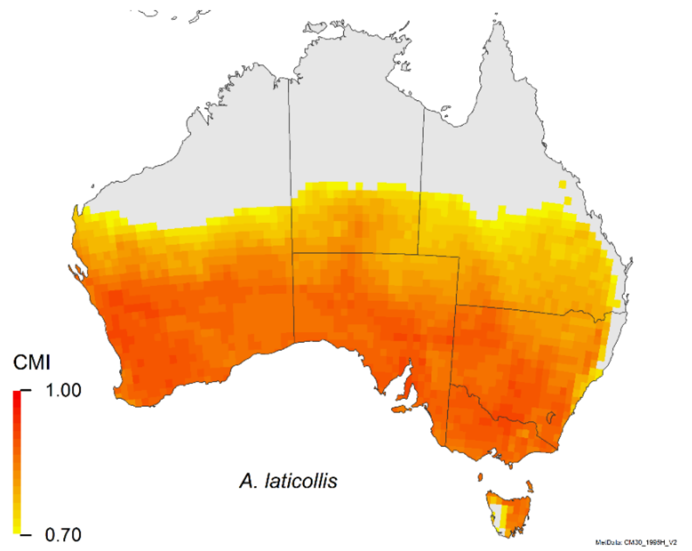
We used the Climate Match (Regional) model of CLIMEX [147] to compare the climates of known locations of each species to the climate in Australia. The underlying assumption in this analysis is that a species can establish in climatically similar locations in a novel area [147-151]. In such analyses, a climate match index (CMI) > 0.7 is accepted to be the minimum for the successful introduction of a species [151; 152]. Thus, for each of the species, we provide a map indicating the CMI to locations where it occurs, only showing regions that have a CMI > 0.7 (Table 14). We used a new, as yet publicly unavailable, 30' CliMond [153] climate grid for the world.

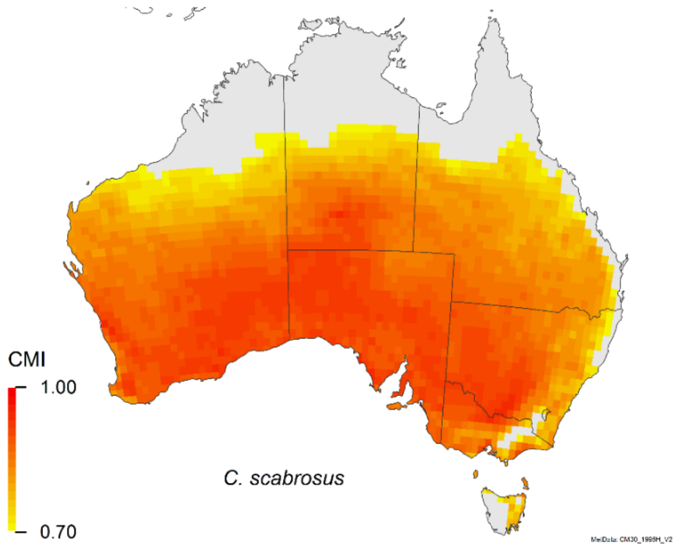
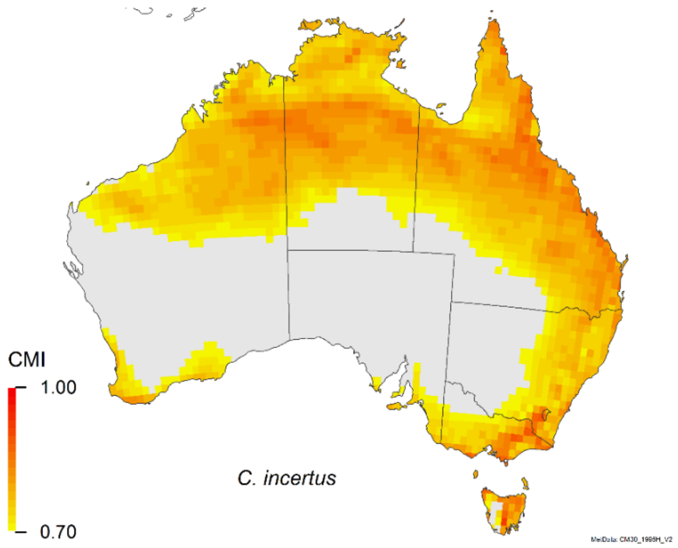
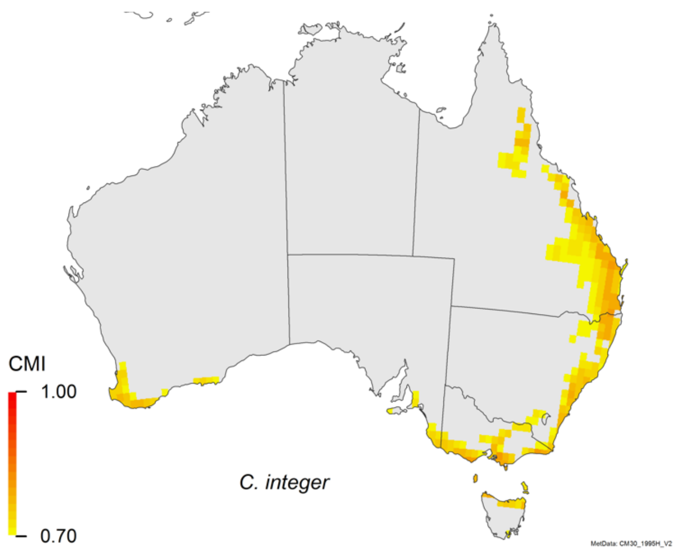
We have not run CLIMEX with any climate change scenarios. Whilst this is possible, all climate change scenarios are based on different emission scenarios, and these are all fraught with conjecture. Increases in temperatures will likely enable the more temperate species to expand their ranges further northwards; and species with a bimodal activity designed to avoid extreme summer temperatures may have more reduced activity peaks, or these peaks may extend further into the winter season if this also warms.

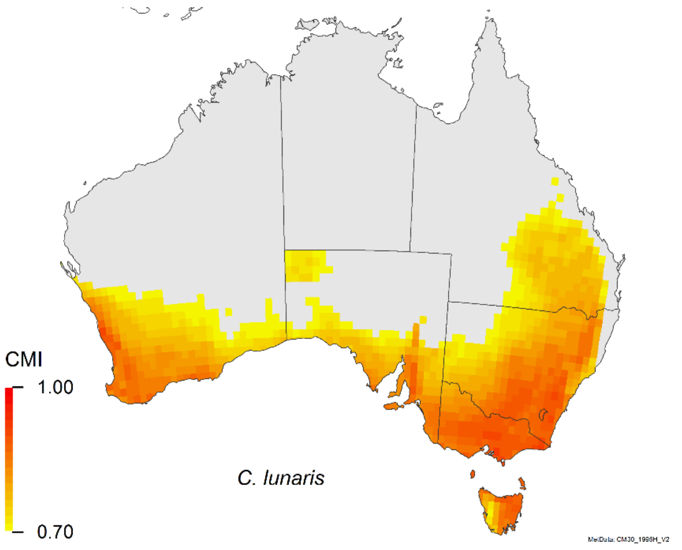
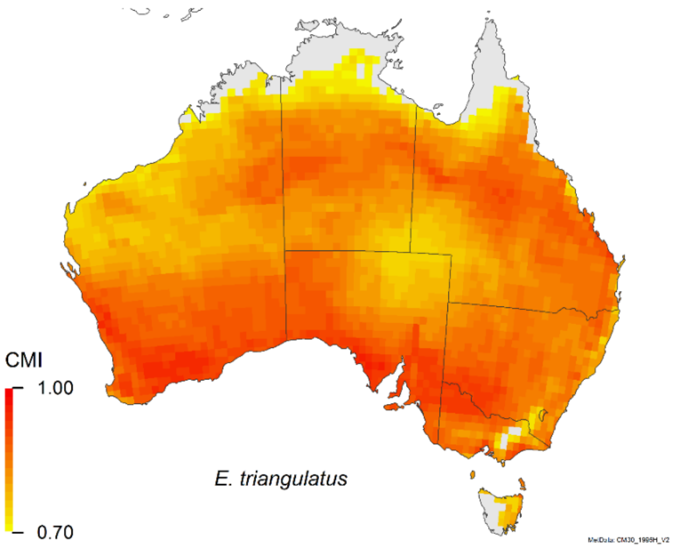
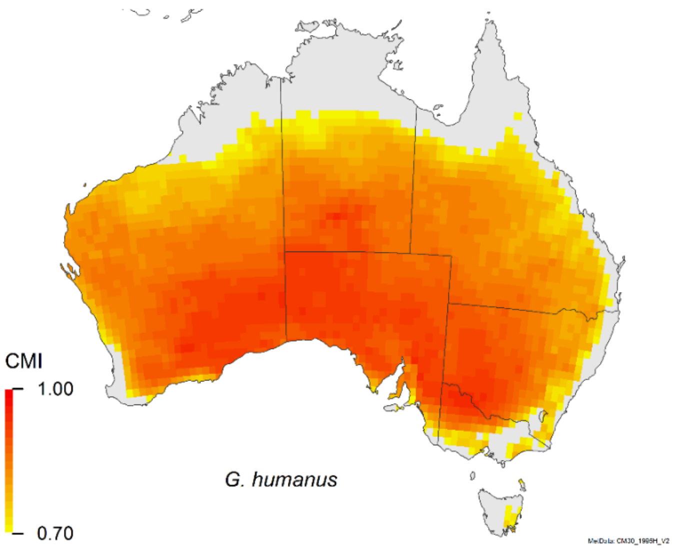
As shown earlier (Section 3.6, Table 8), many species have mechanisms by which to reduce activity in unfavourable climatic conditions. Some species have an obligate winter diapause (*O. nuchicornis*), whilst others appear to be able to reduce their activity in winter, but to capitalise on warm days to continue to feed (e.g., *C. incertus*, *C. lunaris, O. medius* and *O. opacicollis*). In addition, some species can reduce their activity if conditions become unfavourable (*C. scabrosus*, *C. incertus*, *E. triangulatus*, *O. opacicollis*, *S. schaefferi*). Thus, it is very likely that these species will all be able to adapt to Australian climatic conditions. If and when any of these species are imported to Australia, the CLIMEX Match Climates analysis can be repeated at a finer scale to identify and target the most likely places for successful establishment. CLIMEX Compare Locations models could also be built and used to target releases in the correct seasons, and to determine whether seasonal patterns in Australia will be similar to those in the native range. For example, some species (e.g., *C. incertus*, *C. lunaris, O. medius* and *O. opacicollis*) that generally overwinter when it is too cold may be able to be active over winter in parts of Australia where winter temperatures are not as severe.

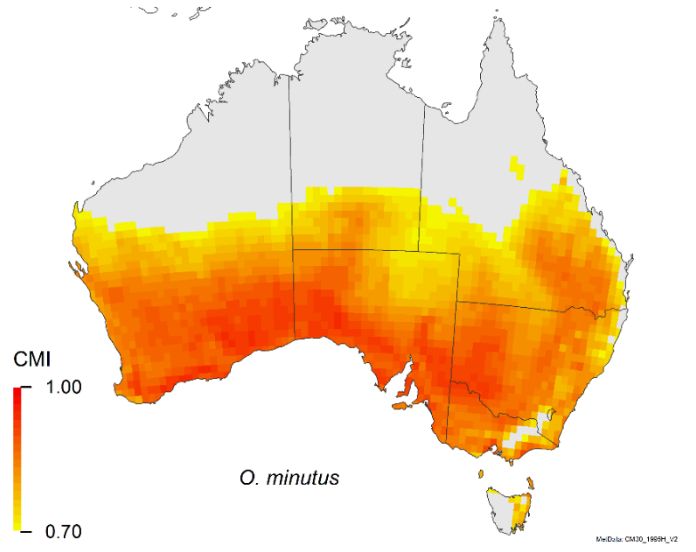
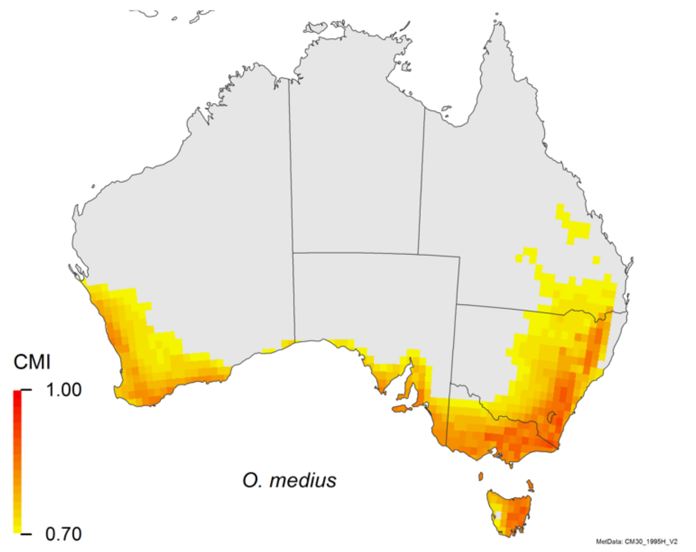
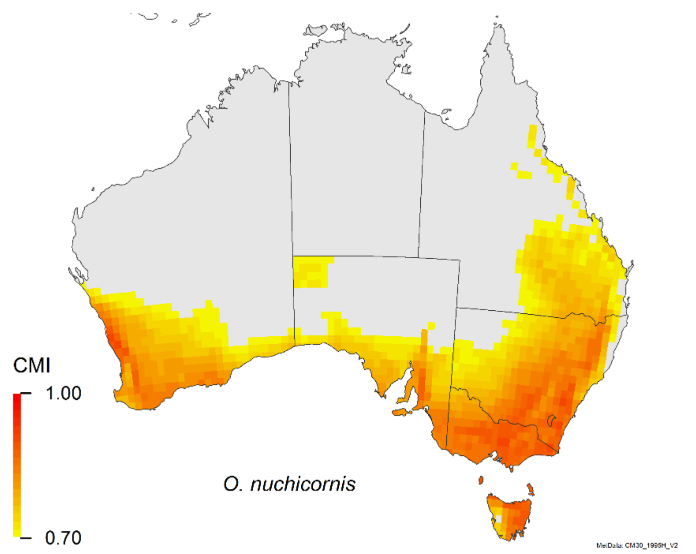
The CLIMEX analysis suggests that both the north and south of Australia have areas that match climates where *C. incertus* occurs. It is possible that this species has a wide climatic tolerance, as location records for Hawaii indicate that it is found at a range of altitudes (sea level to in excess of 1 000 m), and it is found in both relatively dry and moist environments (not all of Hawaii is tropical).

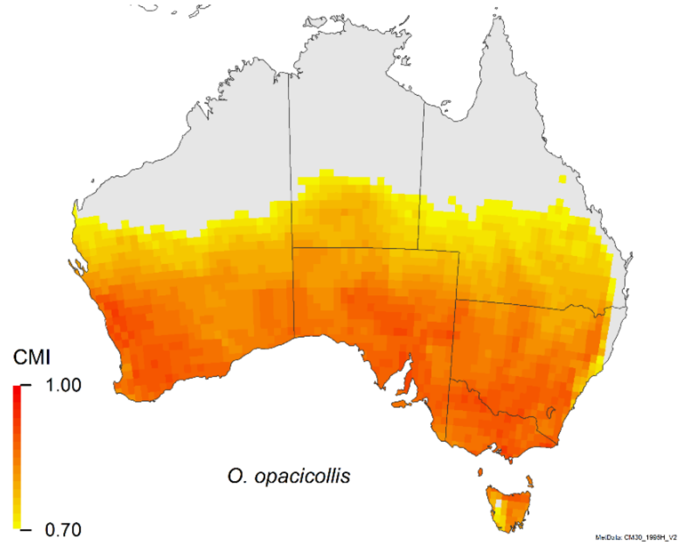
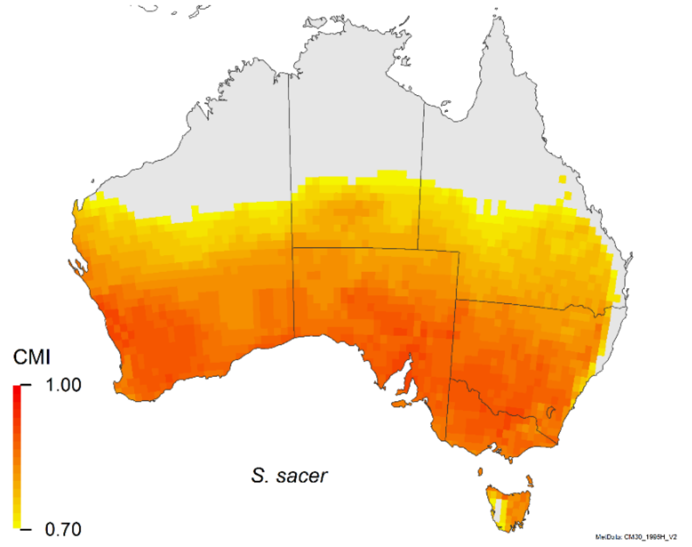
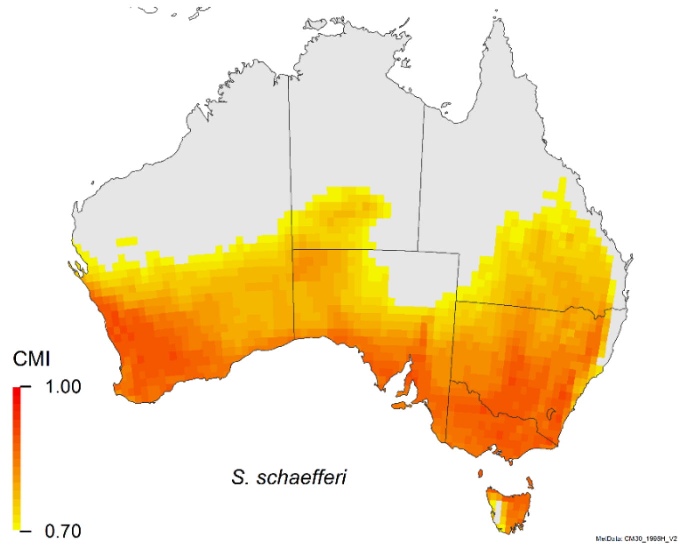
Table 14. Areas in Australia where each species is likely to be able to persist, based on a CLIMEX Match Climates (Regional), using a new CliMond meteorological dataset. Information is provided on the location records used for each species.

Regions of Australia matching the climate where the species is found. Climate Match Index (CMI) > 0.7	Source of species' location records and additional notes on data used
	GBIF.org (08 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.yj2evn 1804 duplicate records removed, based on country, latitude, longitude and altitude
	GBIF.org (08 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.9g2s33 601 duplicate records removed, based on country, latitude, longitude and altitude

Regions of Australia matching the climate where the species is found. Climate Match Index (CMI) > 0.7	**Source of species' location records and additional notes on data used**
	Adrian Davis; Pretoria, South Africa
	GBIF.org (08 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.5fx98h 1009 duplicate records removed, based on country, latitude, longitude and altitude 82 records removed as likely mis-identifications (Colombia, Costa Rica, Ecuador, Guatemala, Honduras, Nicaragua, Panama and Peru) 3 records removed (Australia, Democratic Republic of Congo and Zaire) as unsuccessful introductions or the nature of establishment is unknown 28 records removed (Mexico) as not conforming to distribution in Darling and Génier [73] This analysis utilised location records from Hawaii, Mexico, New Zealand and Western Samoa
	GBIF.org (09 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.zabfqc 17 duplicate records removed, based on country, latitude, longitude and altitude

Regions of Australia matching the climate where the species is found. Climate Match Index (CMI) > 0.7	**Source of species' location records and additional notes on data used**
	GBIF.org (08 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.mve6nk 1643 duplicate records removed, based on country, latitude, longitude and altitude 36 records removed, as basis of record was invalid
	Adrian Davis; Pretoria, South Africa
	Adrian Davis; Pretoria, South Africa

Regions of Australia matching the climate where the species is found. Climate Match Index (CMI) > 0.7	Source of species' location records and additional notes on data used
	Adrian Davis; Pretoria, South Africa
	GBIF.org (8 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.uxcmed 432 duplicate records removed, based on country, latitude, longitude and altitude
	GBIF.org (08 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.4gw8e2 732 duplicate records removed, based on country, latitude, longitude and altitude 39 records removed, as basis of record was invalid 3 records (southern India) removed, as outliers for known distribution

Regions of Australia matching the climate where the species is found. Climate Match Index (CMI) > 0.7	Source of species' location records and additional notes on data used
	GBIF.org (08 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.j863n8 423 duplicate records removed, based on country, latitude, longitude and altitude
	GBIF.org (09 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.vwrxug 232 duplicate records removed, based on country, latitude, longitude and altitude 3 records (Africa) removed as outliers of known distribution and/or because of record issues
	GBIF.org (09 September 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.96tnsv 1030 duplicate records removed, based on country, latitude, longitude and altitude 38 records removed, as basis of record was invalid 3 records (South Africa, Morocco and Egypt) removed as outliers of known distribution and/or because of record issues

7.3 Ability to find shelter

All selected dung beetle species occur primarily in open habitats (grasslands, pastures), and only very rarely in wooded areas (Section 3.8.1, Table 9). They are dependent on dung for breeding and for food (Sections 4.1 and 7.1), and as discussed above (Section 7.1), these species generally prefer cattle, sheep and horse dung. As such, they will only occur in grazing areas where this resource is available. They will not be found in buildings, gardens, horticultural areas, broadacre farms, orchards or vineyards, as these will not have the requisite dung resources. Modified pastures or rangelands would be suitable, providing there is sufficient livestock to consistently produce enough dung for populations to establish.

7.4 Reproduction

The dung beetle species on this application have been selected to have high reproductive capacities. Most species have repeated nesting cycles in a season, with no brooding (parental care) of the young, and multiple eggs laid per season (Section 4, Tables 11 and 12). Three species (*C. incertus*, *C. integer* and *C. lunaris*) have compound nests (multiple eggs) with females caring for the brood balls until the new adults emerge, but *C. incertus* may have up to two nesting cycles in a year [38] and *C. lunaris* is capable of reproducing for two years [39; 40]. Information is lacking as to whether *C. integer* has repeated nesting cycles in a season and/or if females can nest over several seasons/years. However, parental care in these species is likely to improve breeding success, as nest care helps protect the brood balls and increases survival of offspring [90]. Studies in the CSIRO European Laboratory will determine likely rates of reproduction prior to release into the Australian environment.

Reproductive competition from other dung beetle species is not expected to be an issue, as discussed in Section 3.4.2. Dung beetles commonly occur in multi-species assemblages [47; 97-101], and avoid interspecific competition by having differences in feeding and breeding behaviours, patterns of activity (i.e., nocturnal, diurnal or crepuscular) and seasonal activity (i.e., when they are most active and breeding) [100].

7.5 Limiting influences on the species' distribution in Australia

Section 3.4 includes information on predation, competition and resource availability in the native range. As mentioned above, dung availability is key to dung beetle establishment as it is used both as a food source and for reproduction. Competition for dung or mates exists in dung beetles, but as the species in this application have been selected to fill gaps in dung beetle activity, interspecific competition should not be an issue.

7.6 Increased potential for population establishment if more individuals of the species were present in Australia

Introduced dung beetles seem to be less likely to establish in Australia when release numbers are lower. Of the 20 foreign species previously released by CSIRO that failed to establish, 19 had fewer than 8000 individuals released in total, whereas 20 of the 23 species that did establish had more than 8000 individuals released [144 p6]. The low numbers of beetles released for some species was generally due to the small number of eggs imported (for species bred from eggs) or due to difficulties in breeding in quarantine. All efforts will be made to breed as many individuals as possible for release in order to maximise the chances of establishment.

8. Assessment of the potential impact in Australia

8.1 Similar niche requirements to native species

Selected species are not likely to compete with native dung beetle species due to their different niche preferences. The non-native species generally utilise sheep and cattle dung in open habitats, while native dung beetles are adapted to marsupial dung in forest or woodland habitats. There are a number of native *Onthophagus* species that utilise domestic dung, and although the interactions between the native and introduced species are not well understood, populations of native species may have increased with increased dung availability rather than decreased as a result of competition with introduced species [70 p74]. Furthermore, as dung beetles occur in large assemblages with multiple species co-occurring [47; 97-101], and large numbers may be found on a single pad [70 p54, 65-66; 95 p5; 96 p67-68], it is unlikely that new species will exclude native species.

8.2 Transmission of pests and diseases

The importation process for adults of the selected species will mitigate the risk of transmitting exotic pests or diseases. Beetles collected in their native distributions will be starved and cleaned prior to shipping to Australia, and will be kept in an Approved Arrangements (quarantine) facility for the duration of the project. All eggs will be treated with a disinfecting agent (Virkon®) prior to being released from quarantine, reared to adulthood and released into the wild and/or used for the establishment of mass-rearing colonies.

Whilst dung beetles are able to disseminate pathogens that survive their digestive tract or attach to their bodies, it is not clear that dung beetle activity actually increases transmission rates of these infections [154; 155]. Dung beetles have been found to destroy pathogens in dung by altering the abiotic conditions within dung pads, by digesting and burying dung [155], and to reduce the number of infective pathogens on the soil surface as well as their survival [70 p92]. Pathogens that pose a risk to humans but are destroyed by dung beetles include *Cryptosporidium parvum* and *Escherichia coli* [154; 156; 157]. In any event, infected beetles should typically not come into contact with humans, and so their risk of transmitting parasites and diseases to humans is very small. And whilst ball rolling by dung beetles may possibly spread pathogens [158], this is unlikely to occur over a long distance as roller beetles do not bury their dung ball far from the original dung pad, and so again, the risk to humans is minimal.

8.3 Probable prey and food sources

Dung beetles require dung as a food source and for reproduction (see Sections 4 and 7.1), and hence do not attack or prey on wildlife, and neither do they pose any risk to domestic or commercial animals or plants. Some species will feed on carrion (*G. humanus* [110 p9]; *O. nuchicornis* [42; 146]; *S. sacer* [63; Fausek 1906 in 96 p18, Paulian 1938 in 96, p33]) and *S. schaefferi* [Paulian 1938 and Panin 1937 in 96 p33] but this does not pose a risk to live animals, and dung is nonetheless required for reproduction. Similarly, *G. stercorarius* has been reported from rotting fungi [20; 33], *O. nuchicornis* has been recorded to feed on fungi and decaying plant matter[42], and *S. schaefferi* to roll balls of fungal matter [119], but again, this does not pose a risk to any commercial plants and they only utilise dung for reproduction (Lumaret, pers. comm.).

8.4 Impacts on habitat and local environments

In general, dung beetles are considered to have beneficial impacts on habitats, not detrimental ones. Section 3.8.3 highlights evidence that they help prevent runoff of excessive nutrients that could lead to eutrophication of wetlands and aquatic environments [70 p23; 124], Section 5.2 indicates that dung beetles are beneficial to new environments, by removing dung and by improving soil health [22; 24; 70 p13-24; 143], and Section 8.2 highlights the benefits of beetles in reducing pests and diseases [70 p85-94; 155; 159].

Dung beetles can disperse seeds through the transport and burial of the dung of primary dispersers [160-162]. Seeds are dispersed both horizontally and vertically from where they are deposited [163]. Seeds can survive digestion by sheep and cattle, and although in some cases their viability may be reduced (Hogan and Phillips 2011), in some weeds it may be enhanced [164], so the selected dung beetles may be able to spread weeds within the original pasture. Dung beetle seed dispersal has been shown to have both positive and negative effects on germination success [160-162; 165]. It should be noted that weed dispersal by introduced dung beetles has not been reported in the literature, and if introduced dung beetles were highly effective dispersers of weeds, it is likely that property owners would have made CSIRO aware of this during the past 50 years of dung beetle work.

8.5 Potential control or eradication programs

The selected species are intended to be released as a biological control measure for bush flies and dung and they are not considered likely to become environmental pests; thus, no control or eradication programs are considered necessary.

8.6 Behaviours that cause environmental degradation

Dung beetles are not considered to contribute to environmental degradation. As discussed in Sections 3.8.3, 5.2, 8.2 and 8.4, dung beetles are seen to have positive impacts on the environment, not negative impacts.

8.7 Impacts on primary industries

Additional introductions of dung beetles to Australia are expected to improve productivity by incorporating dung nutrients into the soil and thereby increasing soil nutrients, aerating and mixing the soil to increase water permeability and reduce nutrient run-off, and increasing earthworm numbers. The presence of dung beetles was shown to markedly increase pasture production in experimental plots in South Australia, Victoria and Western Australia [70 p14]. Livestock will not generally graze around dung pads, and so dung burial by beetles not only removes the dung, but it also increases nutrient availability to enhance grass growth, thereby increasing pasture productivity [124; 163]. As discussed in previous sections, dung beetles do not pose a risk to humans or to native fauna, they are unlikely to become pests because they are only associated with dung (Section 3.11), they are not likely to transmit parasites and diseases that might negatively impact primary production (Section 8.2), and they have an overall positive impact on habitats and environments (Sections 8.4 and 8.6).

CSIRO is currently participating in a project under the Rural Research and Development for Profit program [166] to gain a more thorough understanding of the ways in which dung beetles can assist primary industry. Dung beetles have been shown to reduce the reproductive success of dung breeding flies, thereby contributing to fly control [70 p88; 159]. Beetle activity in Australia has also been shown to reduce the incidence of livestock intestinal worms (in the *Trichostrongylus* family) [70 p92-93].

8.8 Damage to property

Dung beetles are associated with livestock production in pastures and rangelands, and so do not pose a threat to property or equipment.

8.9 Status regarding social nuisance or danger

Dung beetles are only associated with dung and the species on this list are associated primarily with livestock dung. Therefore, they will not become a social nuisance in any built-up environments (e.g., cities, parks, public facilities).

8.10 Potentially harmful characteristics

As discussed in Section 3.11, dung beetles do not pose a bite or injury risk to other animals or humans. As indicated in Section 8.2, although they may carry pathogens, the risk to humans is minimal, and there is no evidence that they increase transmission of pests and diseases to animals [154; 155]. As discussed in Section 8.2, 9 and 11, appropriate quarantine measures will be taken to prevent disease or pest transmission by imported beetles.

9. Conditions and restrictions applied to reduce negative environmental impacts

Adult beetles of each species will be collected from various localities and air freighted to Australia. All species will be collected form sites where they are abundant. Following collection, adult beetles will be starved for three days to allow them to void any foreign parasites they may have eaten. They will be washed in clean water and any parasites on their bodies will be manually removed. The adults will be segregated by sex then placed in containers of moist vermiculite with breathing holes. These containers will be packed loosely to enhance their chances of survival. The containers will be placed in an insulated cooler box and air freighted to Australia at room temperature. After arrival in Australia, the imported adult beetles will be kept in an Approved Arrangements (AA) facility for the duration of the project. Any beetles that die in an AA facility will be stored in 100% ethanol or autoclaved before disposal, and all eggs released from an AA site will first be surface sterilised in Virkon®.

These importation and AA restrictions will follow Department of Agriculture, Water and the Environment conditions and reduce the risk of negative environmental impacts from parasites or the accidental release of imported beetles. Additional information on collection, importation, and AA practices can be found in Section 8.2, 9 and 11.

10. Rationale for importing dung beetles

10.1 History of the CSIRO dung beetle project

The objective of introducing new species of dung beetles to Australia is to enhance dung burial and reduce the negative impact dung accumulation has in both cattle and sheep farming areas. The use of exotic dung beetles for the biological control of bush flies was first proposed in the early 1960s by CSIRO Entomology. The first round of introductions imported adult beetles and surface-sterilised eggs from Hawaii, Africa, and Europe and ran until 1986 [144 p1]. A second round of introductions, which relied on the importation of adult beetles from Europe, was undertaken from 1990 to 1992 [144 p1]. These two rounds of introductions resulted in the field release of 43 species of Scarabaeine dung beetle, 23 of which are now regarded as being established [70 p50; 144 p6]. A third round of introductions, also relying on adult imports from Europe, was undertaken in 2011-2015 [108]. The fourth and current round of the project began in 2018, importing adult beetles of four additional species from northern Africa, to fill the spring gap in southern Australia.

The multiple benefits of dung beetles have been discussed in previous sections. They help prevent runoff of excessive nutrients that could lead to eutrophication of wetlands and aquatic environments (Section 3.8.4). They are considered to be of benefit in their new environments by removing dung, reducing negative impacts of other pests and improving soil health, and imported dung beetles are considered to be cost-effective, sustainable, and non-invasive (Section 5.2). They have been found to destroy pathogens and reduce the number and survival of infective pathogens on the soil surface, including some that pose a risk to humans (Section 8.2). And finally, they provide positive benefits to the primary industries sector as they increase pasture productivity (Section 8.7).

10.2 Benefits of dung burial

Previous dung beetle introductions have focused on cattle dung burial and bush fly reduction [144 p1; 167 p260], although bush flies can breed in sheep dung [168 p26] and other domesticated and feral animals such as pigs, horses and dogs [169]. Many of the species on this application utilise sheep, cattle and other animal dung, and so they may provide control for both livestock production systems and the environment. We discuss the specific impacts of dung burial in the following two sub-sections.

10.2.1 Soil improvement

The introduction of new dung beetle species is intended to reduce pasture fouling through dung burial, as unburied dung is a source of annoyance to farmers. Cattle dung may remain on the soil surface for between 1 - 16 months in New Zealand, depending on season and rainfall [170], and the annual loss of productive pasture from unburied dung voided by a single cow was estimated to be 0.08 hectare [171]. With the national herd running at 23.4 million [172], this potentially equates to an annual loss of pasture of 1.9 million hectares, although it has more recently been estimated that 200 000 hectares of pasture would be lost annually if cattle dung remained unburied [70 p13]. A Polish study [173] found that unburied sheep dung may cover around 20% of a pasture in a year, although no information was provided on stocking rate. Previous introductions of dung beetles have already helped mitigate this problem: whilst harrowing to disperse cattle and horse dung used to be common in southern Australia, it is now rare [70 p35].

Additional dung beetle introductions are expected to improve soil structure and nutrient levels, and to reduce nutrient runoff into waterways. In Australia, two introduced dung beetles were found to improve the soil and the surrounding landscape by incorporating nutrients, aerating and mixing the soil, increasing water permeability, and preventing nutrient runoff from unburied dung [70 p13-24] , and similar improvements in soil structure and nutrient levels have been observed outside Australia [163; 174]. Other studies have found an increase in plant productivity when dung beetles were present [70 p14-17; 163 p1464; 175; 176], suggesting that dung beetles may assist crop production (Section 8.7). CSIRO is currently participating in a project under the Rural Research and Development for Profit program to gain a more thorough understanding of the ways that dung beetles benefit the soil and improve crop productivity [166].

10.2.3 Control of pest flies

The Australian bush fly (*Musca vetustissima*) is widely known as a major nuisance pest of humans and livestock, although no formal assessments have been made of its economic impact. Bush flies have been implicated in the transmission of trachoma, a very serious problem in Australian Aboriginal communities [70 p34; 177]. The bush fly is present throughout the year in the northern half of the continent, but is unable to survive over winter in southern parts [178]. These areas are re-colonised during late-winter and spring by migrants from the north. The arrival of the bush fly in southern Australia in August-October commonly precedes the emergence of already established spring-active exotic beetles by 1-2 months (Section 10.3, Table 15). Dung is commonly available at this time of the year, enabling fly populations to build up rapidly; therefore, there is a need for winter- and spring-active beetle species.

Only a few native Australian dung beetles utilise the dung of cattle, sheep and horses: most indigenous species occur in forest and woodland habitats [70 p74; 167 p255], and preferentially utilise dung of native animals [70 p74; 167 p255]. Introduced dung beetles can supress this activity through their own use of dung for nesting and feeding. Not only do they disturb the dung pads and remove dung from the soil surface, but they also compete with bush flies by feeding on the dung juices, leaving fly larvae to die of dehydration [70 p85-88].

The introduction of exotic dung beetles for the biological control of dung and bush flies is widely regarded as being highly successful. For example, dairy farmers have benefitted from the absence of flies from milking sheds during summer [70 p34]. However, field control of flies has been difficult to document scientifically, despite laboratory studies demonstrating the effectiveness of dung beetles to reduce fly breeding [179; 180]. Field measurements with entire dung beetle assemblages are more complicated due to fly migration, seasonal weather, dung quality, and the changing seasonal abundance of dung beetle species [e.g., 181; 182] although some studies have demonstrated real reduction in flies emerging from dung pads due to dung beetle activity [183; 184]. In addition, the existence of the current outdoor dining culture in southern Australia has been credited to the activity of dung beetles in suppressing bush fly populations throughout Australia for much of the year [70].

10.3 Gaps in dung beetle activity

An analysis of dung beetle records in Australia has shown that most pastoral areas of Australia are now home to at least one or more species of introduced dung beetle. Whilst various areas may have between 6-10 introduced species, there are many regions where there are only 1-2 established species [144 p5]. Considering that these species have defined activity periods (Table 15), there are many remaining geographical and seasonal gaps in dung beetle activity. With climate change and major droughts that occurred in recent years, there is also a need for species that can withstand more arid conditions.

Table 15. Distribution and activity period of introduced dung beetles in Australia. Data from [144; 185; 186].

Species	**Activity period**	**Distribution in Australia**
Bubas bison	Autumn to spring	WA, SA, VIC, NSW
Copris elphanor	Spring to autumn	QLD: very localised
Copris hispanus	Autumn to spring	WA: very localised
Euoniticellus africanus	Spring to autumn	NSW, QLD
Euoniticellus fulvus	Spring to autumn	WA, SA, VIC, NSW, TAS
Euoniticellus intermedius	Spring to autumn	WA, SA, NT, NSW, QLD
Euoniticellus pallipes	Spring to autumn	WA, SA, VIC, NSW
Geotrupes spiniger	Spring to early winter	VIC, NSW, TAS
Liatongus militaris	Spring to autumn	QLD, NT, NSW (northeast corner)
Onitis alexis	Spring to autumn	WA, SA, NT, VIC, NSW, QLD
Onitis aygulus	Spring to autumn	WA, SA, VIC, NSW
Onitis caffer	Autumn/winter	WA, NSW, QLD
Onitis pecuarius	Late spring to autumn	NSW, QLD (southeast)
Onitis vanderkelleni	Spring/summer	QLD: very localised
Onitis viridulus	Spring to autumn	QLD, NT, WA (northeast corner)
Onthophagus binodis	Late spring to autumn	WA, SA, VIC, NSW, QLD, Tas
Onthophagus gazella	Spring to autumn	WA, NT, SA, NSW, QLD
Onthophagus nigriventris	Spring to autumn	NSW, QLD
Onthophagus obliquus	Beginning rain season	QLD: very localised
Onthophagus sagittarius	Summer	QLD (coastal), NSW (northeast corner), NT
Onthophagus taurus	Spring to autumn	WA, SA, VIC, NSW, TAS
Sisyphus rubrus	Spring to autumn	QLD, NSW (northeast)
Sisyphus spinipes	Spring to autumn	QLD, NSW (northeast)

A map of all dung species recovered and reported [144] was produced. This was compared to maps of cattle areas and densities [187] and sheep areas and densities [188] to identify regions with relatively low beetle activity for the livestock present. Areas were categorised by predominant Australian climate regions [144 p11]. The key seasonal gap identified by this analysis was winter: winter-active beetles are required in all the areas identified as needing additional dung beetle species to effectively deal with dung. There is also a need for species that can withstand both summer and winter in more arid conditions, as many of the currently established species cannot withstand prolonged hot and dry conditions: during the recent drought, dung beetle populations were observed to plummet. Five major seasonal/geographical gaps were identified:

Gap A: winter in wet summer, dry winter rainfall zone

Gap B: winter in wet summer, low winter rainfall zone

Gap C: winter in wet winter, low summer rainfall zone

Gap D: winter in arid rainfall zone

Gap E: summer in arid rainfall zone

It is important to note that other regional gaps exist, and these should also be filled where possible. This could be achieved with the species selected below, as most have different activity periods (Section 3.8.2, Table 10) and the climate match analyses indicate that broad regions of Australia have climates similar to those in the native ranges of the species (Section 7.2, Table 14).

10.4 Species selection

Dung beetle experts were consulted and the literature was reviewed to identify species suitable for these gaps, resulting in the species in this application.

By combining the five seasonal and geographical gaps identified (Section 10.3) with information on seasonality (Section 3.8.2, Table 10) and areas in Australia that match the climates where each species is found (Section 7.2, Table 14), we were able to identify the gaps for which each species could potentially be suited (Table 16).

Table 16. Selected species with targeted dung beetle activity gap.

Species	Gaps	Notes
Geotrupes stercorarius	B, C	Spring to autumn activity, but could be active earlier/later in a warmer climate
Ateuchetus laticollis	B, C, D	Spring to autumn activity, but could be active earlier/later in a warmer climate
Cheironitis scabrosus	B, C, D, E	Spring to autumn activity, but could be active earlier/later in a warmer climate
Copris incertus	A, B, C	Winter active in parts of New Zealand, could be active earlier/later or even over winter in a warmer climate
Copris integer	A, B, C	Active all year around
Copris lunaris	B, C	Spring to summer species, but remains active underground in winter
Euoniticellus triangulatus	A, B, C, D, E	Active all year around
Gymnopleurus humanus	B, C, D, E	Summer rainy season activity (but collected all year)
Onitis minutus	B, C, D	Active in May-June in South Africa
Onthophagus medius	B, C	Spring to autumn activity, but could be active earlier/later in a warmer climate
Onthophagus nuchicornis	B, C	Spring to autumn activity, but could be active earlier/later in a warmer climate

Species	Gaps	Notes
Onthophagus opacicollis	B, C, D	Spring to autumn activity, but could be active earlier/later in a warmer climate
Scarabaeus sacer	B, C, D, E	Spring to autumn activity, but could be active earlier/later in a warmer climate
Sisyphus schaefferi	B, C, D, E	Spring to autumn activity, but could be active earlier/later in a warmer climate

There are few dung beetle species that are active in winter; therefore, many of the species selected are spring-autumn active. However, we anticipate that these species could be active earlier in spring or later in autumn in a warmer Australian climate. Until beetles are imported and reared in Australia, we are unable to unequivocally identify the best winter-active beetles. However, potential species include *C. incertus* (gaps A-C), *C. integer* (gaps A-C), *C. lunaris* (gaps B,C), *E. triangulatus* (gaps A-D; E is a summer gap), and *O. minutus* (gaps B-D).

Although *C. incertus* failed to establish in previous introductions [144 p39], this may have been due to low numbers of beetles released at each site or because of an insufficient volume of high-quality dung (Section 5.3). In addition, the climate matching analysis (Section 7.2, Table 14) indicates that some of these release sites may also have been in marginally suitable areas. *Copris incertus* has been observed breeding in July (winter) in Auckland and further north in New Zealand in mild winters (SA Forgie, pers. comm.), and so it is likely to be able to feed and breed in warmer Australian winters.

Adults of *C. lunaris* feed on dung in feeding chambers or on soil surface during warm weather in winter [40], and winter temperatures in southern Australia are likely to be warmer than many regions where it occurs in in its native range. Even if it doesn't actually breed in winter, it may be able to extend its breeding activity to start earlier in spring and end later in autumn, and it could potentially still contribute to some dung removal by feeding in winter. As indicated previously, *C. lunaris* likely failed to establish when it was previously introduced due to the low number (96) of beetles released over a three-month period (Section 5.3). These data support the notion that locations for releases must be correctly identified, that the timing of these releases must be optimised, numbers of beetles released at any one time must be sufficiently large, and that sufficient volumes of quality dung resources are available when beetles are released.

Euoniticellus triangulatus is found throughout the year in Kenya and South Africa [53; 81] and *O. minutus* is active in May-June in South Africa [11 p372]. If climatic conditions where they are introduced in Australia are not as extreme as in their native ranges, these species may well be active throughout the Australian winter. Other species that may be suitable for Gaps A-D, but are unlikely to breed in winter, may nonetheless be able to extend their breeding season (earlier in spring, later in autumn), as discussed above for *C. lunaris*. These include *G. stercorarius*, *A. laticollis*, *O. medius*, *O. nuchicornis*, *O. opacicollis*, *S. sacer* and *S. schaefferi* (Table 16).

To fill the hot arid summer gap E, *C. scabrosus*, *E. triangulatus*, *G. humanus* and *S. sacer* appear to be good candidates, based on the climate matching analysis (Section 7.2, Table 14) and Table 16. These species may be able to better tolerate the arid climate than the species already introduced here. In addition, they should also thrive in several of the other regions, and in all areas be able to augment the diversity of the current beetle assemblages.

10.5 Numbers of beetles to be imported

We expect to import at least 500 male-female pairs of beetles of each species. They are to be collected from areas where they are locally abundant (Section 9). This number should be sufficient to establish a population in the AA site.

10.6 Male and female interactions

Male and female dung beetles only interact with one another when reproducing, with the level of interaction varying according to the species, as detailed in Section 4.

Adults will be segregated by sex for shipping (Section 9). For breeding purposes in Canberra, we will consider the breeding requirements of each species to determine the conditions that will optimise egg production.

10.7 Breeding: management and control

The purpose of importing these beetles is to breed them to better understand their biology and lifecycles, so as to enable mass-rearing for release. There will be no surplus of beetles from the breeding program, as all viable dung beetles will be required for release. Imported dung beetles that die in the AA facility will be kept in 100% ethanol or autoclaved before being disposed of, as per Department of Agriculture, Water and the Environment permit requirements. The number of beetles kept at any time on the premises is unknown as it will depend on the number of beetles imported and successfully reared.

Because we will be importing a large number ($\geq$ 500) of beetles of each species, collected from different localities where they are abundant (Section 10.2), we will begin the breeding program with a relatively large population for each species. This will ensure that there is sufficient genetic diversity present.

10.8 Other potential uses

Separate from CSIRO, businesses have been set up to provide previously introduced dung beetle species such as *B. bison* to farmers looking for a way to manage dung. These businesses should not have a negative impact on the continuation of the dung beetle project. Rather, by establishing colonies of already introduced species to areas with appropriate climates and habitats, this commercial activity will assist the dung beetle project aims of livestock dung burial and bush fly suppression.

The Nagoya Protocol of the Convention on Biological Diversity is likely to affect the commercial sale of introduced dung beetles by enforcing the sharing of benefits from the utilisation of genetic resources. For example, businesses that sell introduced dung beetles to farmers may be required to share profits with the countries the beetles are native to. The Nagoya Protocol should not affect the dung beetle project as the aim is for public good. Consultation with each country will be made prior to importation through the official channels.

10.9 Collection of material

Beetles will be collected from areas where they are locally abundant (Section 9).

11. Guidelines on how species should be kept

11.1 Transport

Adult beetles of each species will be air freighted to Australia. After arrival in Australia, the imported adult beetles will be kept in an AA facility for the duration of the project.

11.2 Containment, management and release

Breeding containers in the dung beetle facilities in Canberra will contain male-female pairs, and will be provisioned with sufficient dung to minimise combat for resources, to prevent overcrowding, and to maximise egg production. Because each species will have different requirements for maximising egg production, the set up for each species might differ (size of container, number of pairs per container, substrate used, humidity, temperature and light regimes, etc.). The number of beetles that will be kept at any time on premises is unknown and will depend on the number of beetles imported and successfully reared.

There will be no excess progeny in the breeding program, as all viable dung beetles will be required for release. Any imported dung beetles that die in the AA facility will be kept in 100% ethanol or autoclaved before being disposed of, following Department of Agriculture, Water and the Environment guidelines.

Release sites will be chosen by selecting climatically optimal sites on properties where owners are committed to maximising beetle establishment, such as avoiding the use of parasiticides. Beetles will be released when they are sexually mature and physiologically synchronised with the local season. Release numbers will vary according to the numbers reared, but the aim will be to release a minimum of 500 male-female pairs of each species at any given site. Preference will be given to paddocks containing enough cattle to provide a sufficient quantity of high-quality dung, and in which there is a well-established cattle campsite.

12. State/Territory controls

None of the species on this application are prohibited by legislation or classed as a pest species by either the Commonwealth or any of the states and territories. Different websites required searching in different ways. In some cases, each species was individually searched for; in others, the family name Scarabaeidae was used; still others provided a list to scroll through. The following web sites were used to ascertain pest status of the species in the Commonwealth and in each state or territory:

- Commonwealth: http://www.environment.gov.au/biodiversity/threatened/key-threatening-processes/novel-biota-impact-on-biodiversity
- ACT: https://www.environment.act.gov.au/__data/assets/pdf_file/0008/575117/PAMS_WEB.pdf
- New South Wales: https://www.environment.nsw.gov.au/threatenedspeciesapp/
- Victoria: https://agriculture.vic.gov.au/biosecurity/pest-insects-and-mites
- South Australia: https://www.pir.sa.gov.au/biosecurity/introduced-pest-feral-animals
- Tasmania: https://dpipwe.tas.gov.au/invasive-species/invasive-animals/invasive-species-other-pests
- Western Australia: https://www.agric.wa.gov.au/pests-weeds-diseases/pests/pest-insects
- Northern Territory: http://pestinfo.nt.gov.au/
- Queensland: https://www.daf.qld.gov.au/business-priorities/plants/field-crops-and-pastures/broadacre-field-crops/integrated-pest-management/a-z-insect-pest-list

All species are proposed to be added to the Live Import List under the Biosecurity Act 2015. Import permits will need to be obtained from the Department of Agriculture, Water and the Environment.

AA facilities are already in place at CSIRO, as the importation of other dung beetles has been approved previously.

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