



Manaaki Whenua
Landcare Research

Evaluation of the effectiveness of dung beetles in improving the environmental health of land and rivers within Tairāwhiti

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Evaluation of the effectiveness of dung beetles in improving the environmental health of land and rivers within Tairāwhiti (Gisborne District)

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Summary

Project and Client

- Gisborne District Council was awarded an Envirolink Medium Advice Grant (1828-GSDC147) from the Ministry of Business, Innovation and Employment to evaluate the effectiveness of dung beetles in improving the environmental health of land and rivers in three catchments in the Tairiawhiti (Gisborne) region. Manaaki Whenua – Landcare Research was subcontracted to undertake this research.

Objectives

- Identification of characteristics of land use, soil type, climate, topography, and catchment character leading to successful dung beetle establishment in catchments in the Gisborne region where ruminant stock are common.
- Assessment of potential risks, constraints and environmental benefits associated with dung beetle release by review of case studies of dung beetle releases globally.
- Evaluation of the environmental benefits of releasing dung beetles in the Wharekopae, Motu and Waiapu catchments.
- Assessment of two privately funded releases that have occurred in the district.
- A workshop at Gisborne to provide guidance on establishing dung beetles on their land for exemplar farmers in the three catchments (who have expressed interest in dung beetle releases on their properties).
- Advice and recommendations to GDC on the best and most cost-effective ways of implementing dung beetle releases within the three catchments.

Results

- Land use: the new dung beetle species approved for release in New Zealand in 2011 strongly prefer open habitats, and need a regular, substantial supply of fresh dung from stock (primarily cows, sheep, and horses).
- Soils: almost all the 11 new species of dung beetle will be capable of burrowing into the more common soils in the Gisborne region.
- Topography is unlikely to limit dung beetles but high hills, large water bodies may limit dispersal. Beetles may not establish well at higher altitude sites, but low stocking rates at these sites already preclude any substantial benefits from dung beetle activity.
- Climate: most species are expected to survive in most New Zealand pastures although two African species *Digitonthophagus gazella* and *Onitis alexis* are expected to be most suited to the North Island, including the Gisborne Region.
- Seasonality: The range of species selected for release in New Zealand includes species that are predominantly active in all four seasons.
- Benefits to pasture: our global review revealed quantified benefits to pastures from dung beetles that were nearly all positive, but variable in magnitude, including increased dung removal (resulting in less area of fouled pasture), improved soil structure and water infiltration, and increased plant productivity.

- There are likely to be benefits from dung beetles to human health (reduced disease transmission from exposed dung on pastures) and animal health (e.g. reductions in bovine Tb, Johne's disease, parasitic nematodes).
- Reductions in greenhouse gases may occur with dung beetle activity, but the effects will be minor compared with other agricultural emissions such as gases breathed out by stock after enteric fermentation.
- Risks of negative interactions with indigenous biota are very low because large numbers of dung beetles will not be found in habitats on which the New Zealand biota depends: high numbers of the new species of dung beetles will only be found on intensively grazed pastures with high numbers of stock:
- There is limited information on the effects of dung beetles on leaching of nutrients and pathogens through soils, but preliminary data in New Zealand have shown no elevated levels of C, N or bacteria in leachate from the base of deep soil cores.
- Catchment level evaluation: globally, no experimental studies have been conducted on the effects of dung beetles at farm- or catchment-level scales. The only catchment study of benefits from dung beetles of which we are aware is modelling in New Zealand by Dymond et al. (2016), and the dung beetle input to this model used only estimated parameters. There is potential for monitoring at paddock, farm or catchment scales but logistic issues and costs escalate rapidly with scale. Evaluation projects need careful design, taking into account aims, resources, and time-frames.
- Assessment visit: two sites were visited in May 2018 but no dung beetles of the species released were recovered. Establishing populations can be hard to detect for a few years, so this negative result does not necessarily mean the releases have failed.
- A workshop in May 2018 held by Gisborne District Council and run by Dr Shaun Forgie to provide guidance on establishing dung beetles on their farms.
- Implementation of dung beetle releases: there are methods for making farms "dung beetle friendly", e.g. being careful about choice and application of drenches. A demonstration farm, perhaps with some GDC-funded releases, might generate local interest in farmers. Dung beetle species are commercially available in New Zealand, although in time, local collection/re-distribution of dung beetles may be possible.

Recommendations

- Releases of dung beetles should be matched to the environments in which they are intended to operate, although there are limitations, given the restricted range of species currently available in New Zealand.
- GDC can use benefits/risks to support investment in dung beetles and answer any public concerns over the release of new species of dung beetles in the region.
- GDC should engage with ongoing dung beetle research to facilitate monitoring at mesocosm, paddock, farm and/or catchments levels.
- GDC can use this report to provide guidance to farmers on the best and most cost-effective ways to obtain benefits from dung beetles across the three catchments.
- One farm could be considered as a sampling site under the Australian dung beetle programme that has just started. The resources for monitoring this site would be covered under the new programme, and it could be a good way to up-skill GDC staff and farmers into small-scale evaluation methods.

1 Introduction

Dung beetles search out the faeces of animals, which they use for food and reproduction. The species being introduced to New Zealand make tunnels in the soil beneath the faeces, which they then bury to lay eggs in. As the eggs hatch the grubs feed on the dung so they break it down and eventually turn it into a sawdust-like material that adds to the fertility of the soil structure while all the time getting rid of dung sitting on top of the ground.

Many countries in the world, including New Zealand, do not have dung beetles that are adapted to utilise the dung of the exotic ruminants that we use as farm stock. Hence, over 100 species of non-native dung beetles have been deliberately released into at least seven countries (Hanski & Cambefort 1991; Simmons & Ridsdill-Smith 2011). These provide a range of beneficial ecosystem services, e.g. to reduce pests such as flies and parasitic nematodes, and to promote bioturbation, which can potentially enhance herbage yields and water quality (Hughes et al. 1975; Nichols et al. 2008; Beynon et al. 2015).

New Zealand has forest-dwelling native dung beetles that do not live in pasture, and although they are generalist dung feeders, this strict habitat restriction means they are totally ineffective at tackling ruminant dung in pastures (Ewers et al. 2007; Jones et al. 2012). One exotic species of dung beetle, the sub-tropical Mexican Dung Beetle was released in New Zealand in 1956 but is only found in the warmer climates at the top of the North Island (Dymock 1993). There are also several species of dung beetles that have arrived by accident, but these are small and do not bury dung effectively (Forgie 2009).

Despite the formal risk assessment process conducted by the Environmental Risk Management Authority (ERMA), the decision to grant approval for unconditional release of 11 new species of dung beetles was publicly questioned. Concerns included the spread of infectious diseases affecting both livestock and public health. The potential benefits and perceived risks of introducing new non-native dung beetle species are reviewed in this report.

To date, seven of these species have been imported and released in New Zealand pastures as part of an ongoing introduction programme, namely: *Bubas bison* (L.), *Copris hispanus* L., *Digitonthophagus gazella* (F.), *Onitis alexis* Klug, *Onthophagus binodis* (Thunberg), *Onthophagus taurus* (Schreber) and *Geotrupes spiniger* (Marsham) (Fig. 1). The other approved species are: *Bubas bubalus* (Olivier); *Euoniticellus fulvus* (Goeze); *Copris lunaris* (L.) and *Onthophagus vacca* (L.).

Given the complexities associated with the release of dung beetles (e.g. multiple species, benefits and risks) Gisborne District Council commissioned this report to get advice on new dung beetle species.

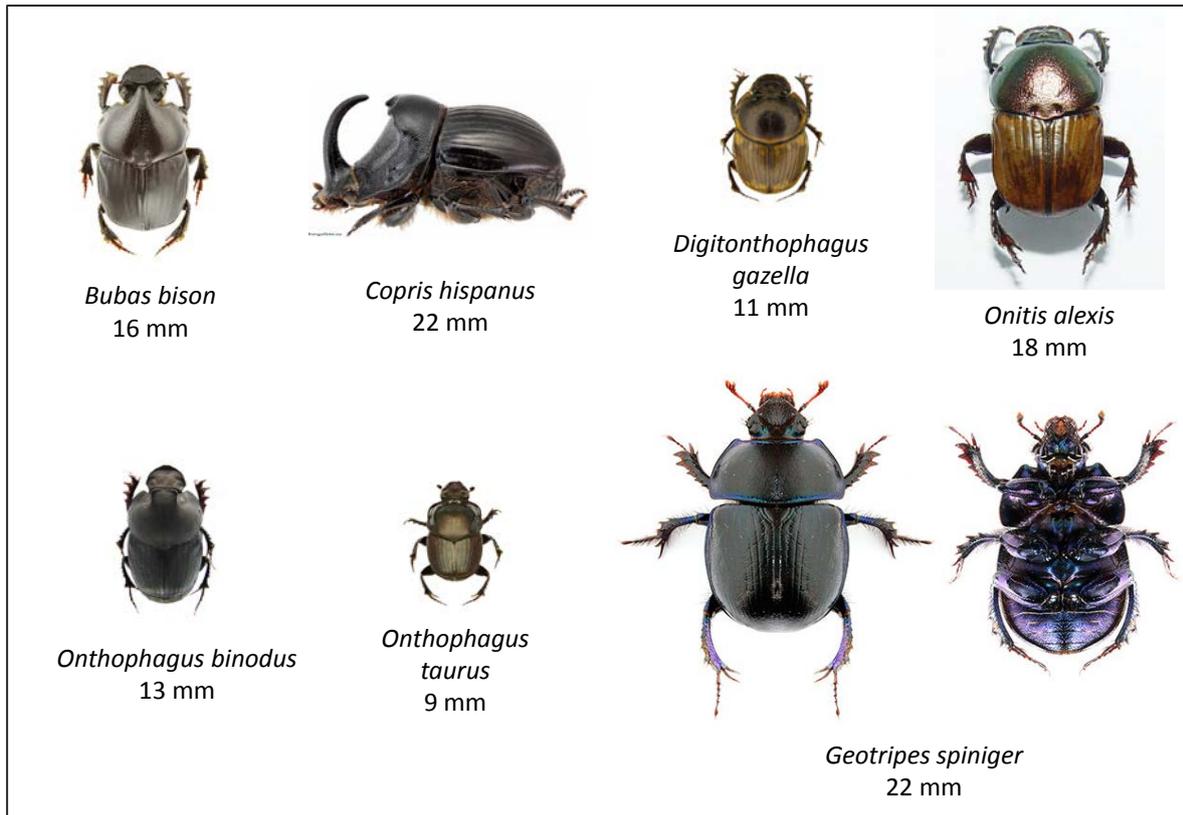


Figure 1. The new dung beetle species released in New Zealand by 2018.

2 Objectives

- Identification of the main characteristics of land use, soil type, climate, topography, and catchment character leading to successful dung beetle establishment in catchments in the Gisborne region where ruminant stock are common.
- Assessment of potential risks, constraints and environmental benefits associated with dung beetle release by review of case studies of dung beetle releases elsewhere in New Zealand and overseas.
- Evaluation of the environmental benefits of releasing dung beetles in the Wharekopae, Motu, and Waiapu catchments.
- Assessment of two privately funded releases that have occurred in the district.
- A workshop (to be held in Gisborne) to provide guidance for exemplar farmers in the three catchments (who have expressed interest in dung beetle releases on their properties).
- Advice and recommendations to GDC on the best and most cost-effective ways of implementing dung beetle releases within the three catchments.

3 Methods

Literature searches were carried out using Google, Google Scholar, and the Web of Science. The main source of information on the potential effects of dung beetles on human health was a review by the Institute of Environmental Science and Research (ESR) for the Ministry of Health of the New Zealand Government (Mackereth et al. 2013). Information on Johne's Diseases came from literatures searches and from the Johne's Advisory Group website (JAG 2018). The main source of information on the potential effects of dung beetles on gastrointestinal nematodes of stock was a comprehensive review carried out for the Dung Beetle Technical Advisory Group (Fowler 2013).

A one-day workshop was organised by the Gisborne District Council in May 2018 and held at the council offices. The workshop aimed to provide guidance for farmers with interests in releasing dung beetle on their properties.

Assessment visits were made to two properties in the region where dung beetles had been released. Release records were accessed to ascertain which species had been released, and details of the release methods and release sites obtained from the landowners. At the Rata Hills site a visual search was carried out for 2–3 hours over an approximately 1-km distance downhill from the release sites looking for soil casts and disturbed dung crusts (in cow/horse dung piles). At the Kakanai Road site, the visual search covered the entire 20-ha property, with most cow and horse piles examined for soil casts and disturbed dung crusts.

Information on implementation and cost-effectiveness for establishing dung beetles was obtained from the Dung Beetle Innovations website <https://dungbeetles.co.nz/>

4 Results

4.1 Identification of the main characteristics of land use, soil type, climate, topography, and catchment character leading to successful dung beetle establishment in catchments in the Gisborne region where ruminant stock are common

4.1.1 Land use/dung type/topography

The main constraints on the type of land that the introduced dung beetles will inhabit are i) they have a strong preference for open habitats such as pasture, and ii) they need a regular and substantial supply of fresh dung. Different dung beetle species prefer different dung types. Although field specificity records indicate many of the new species of dung beetles released in New Zealand prefer cow dung (Table 1) they will also feed on the dung produced by other large herbivores, such as alpacas, deer, horses, and sheep. The trophic preference can vary within a species, for example, one study reported *Euoniticellus fulvus* prefers cow dung over horse dung and another found the opposite was true (Table 1). This may be a result of variation in the diet of the herbivores influencing the attractiveness of the dung (Barbero et al. 1999). Exploitation can vary according to dung consistency, for

example, *O. taurus* exploits only big lumps of sheep dung; not separate pellets except when they form humid heaps (Dr Jean-Paul Lumaret, Centre d'Ecologie Fonctionnelle et Evolutive, Montpellier, pers. comm.). Many of the species can cope with liquid dung produced by dairy cattle. Indeed, adult dung beetles feed on the fluids in dung and filter out small particulates (Hanski & Cambefort 1991; Holter et al. 2002). By contrast, dung beetle larvae generally are adapted to feed on coarser-grained material in the dung ball that adults produce for the larvae to develop in (Hanski & Cambefort 1991).

The introduced dung beetles are unlikely to be limited by topography *per se*, but high altitude hills, or large water bodies, are likely to be barriers to dispersal (Martín-Piera et al. 1992), and release strategies should consider this. The introduced species may not inhabit high altitude country, but the lack of pasture/intensive grazing would also preclude much benefit accruing from the new dung beetles even if they did establish at these sites.

Table 1. Dung types utilised by the new dung beetle species approved for release in New Zealand. †Species already introduced and available for release in New Zealand

Species	Host dung *Preferred dung (if data indicate a strong preference)
<i>Bubas bisort</i> †	Cow ^{1,2} ; *cow, horse, sheep ³ ; cow, sheep/goat, horse ⁶
<i>Bubas bubalus</i> (Olivier)	Deer ¹ ; *horse, cow ⁴ ; cow, sheep/goat, horse ⁶
<i>Digitonthophagus gazella</i> †	*Cow ⁵
<i>Euoniticellus fulvus</i>	*Fallow deer, horse, cow, wild boar ¹ ; *horse, cow ⁴ ; *horse, cow, sheep/goat ⁶ ; *cow, horse, deer, wild boar ⁷ ; cow ⁸
<i>Geotrupes spiniger</i> †	Deer ¹ *cow, horse, sheep ³ ; *cow, sheep ⁸
<i>Copris hispanus</i> †	Cow, horse ^{1,4} ; cow*, sheep, horse ³ ; cow, sheep, goat, horse ⁶
<i>Copris lunaris</i> (L.)	*Cow, sheep ^{6,8}
<i>Onitis alexis</i> †	*Cow/buffalo ⁹
<i>Onthophagus binodis</i> †	Horse ⁹ Cow ¹⁰
<i>Onthophagus taurus</i> †	*Cow, *fallow deer, deer, horse, wild boar ¹ ; *cow, horse, sheep ² ; cow, sheep/goat, horse ⁶ ; *cow, horse, deer, wild boar ⁷ ; *cow, sheep ⁸
<i>Onthophagus vacca</i> (L.)	*Cow, *fallow deer ¹ ; *cow and *sheep, horse ³ ; *cow, horse ⁴ ; cow, sheep/goat, horse ⁶ ; *cow, sheep ⁸ ; alpaca ¹¹

¹Martin-Piera and Lobo (1996); ²Kirk (1983); ³J-P Lumaret, pers. comm.; ⁴Dormont et al. (2004); ⁵Miranda et al. (2000); ⁶Kirk and Ridsdill-Smith (1986); ⁷Barbero et al. (1999); ⁸Wassmer (1995); ⁹Holter et al. (2002); ¹⁰Ridsdill-Smith (1993); ¹¹Arnaudin (2012)

4.1.2 Soil and climate

A range of soil types are present in the Gisborne region (Fig. 2) of which Brown, Gley, Pallic, Pumice and Recent soils are predominantly used for pastoral farming. Within these broad classifications, the most common soil orders are brown and recent soils that are sandy, silt or clay loams (Table 2).

Some dung beetles show preferences for certain soil types. However most species selected for introduction into New Zealand can cope with both heavy clay soils and light sandy and silty soils (Table 3), although soil type may influence how deep they are able to tunnel.

Therefore, almost all of the new dung beetle species will be capable of burrowing into the more common soils in the Gisborne region.

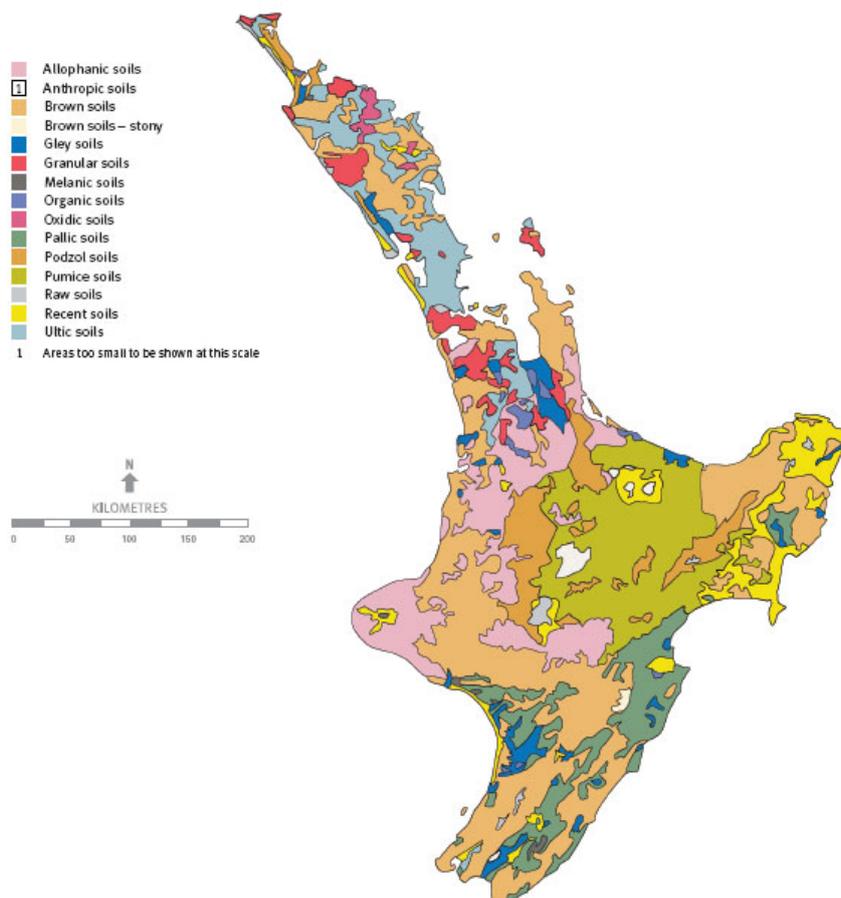


Figure 2. Soils of New Zealand (from Van Bunnik et al. 2007).

Table 2. Main soil types in pasture land in the East Cape Region (Gisborne District). From: <http://www.nzsoils.org.nz/PageFiles/233/SoilsOfNZ%20By%20Region.pdf>

Soil order	Soil name	Soil characteristics (top ~30 cm)
brown	Kiore Hill Soil	Gritty silt loam; gravelly silty clay loam with 10% weakly weathered angular mudstone fragments
	Whakawai Hill Soil	Sandy loam with few sandstone fragments
recent	Oruataiaka Hill Soil	Silt loam with weakly weathered greywacke gravels
	Waiherere Silt Loam	Silt loam

New Zealand has an Oceanic climate (Cfb), according to the Köppen classification (the most widely used system for classifying the world's climates), as do regions in Australia (notably southern NSW, Vic and Tas). The dung beetles selected for introduction in NZ are native to areas in Europe or South Africa (see Table 3) that belong to the same climate zone (see Fig. 3 for a global map of Cfb regions). Moreover, many have already been established in Cfb regions of Australia (NSW, Tas, Vic; Table 3; Fig. 3). Most species

therefore are expected to survive in most New Zealand pastures. However, two African species, *D. gazella* and *O. alexis*, that established on mainland Australia, failed to establish in Tasmania and are therefore expected to be most suited to the upper North Island of New Zealand, including the Gisborne Region.

However, predicting distributions based on climate matching may underestimate environmental tolerance because the native range of a dung beetle may not necessarily be restricted by climate alone (for example, resource limitation or poor dispersal may constrain distribution; Duncan et al. 2009). As such, dung beetles may turn out to have a greater environmental tolerance/potential distribution than might be anticipated in New Zealand based on climate match alone.

Table 3. Soil preferences and native and introduced ranges of the dung beetle species approved for release in New Zealand

Species	Soil preference	Country of Origin	Introduced range in Australia
<i>Bubas bison</i>	Compact soils, clay or loam, including heavy clay soils that flood in winter	Spain, France	NSW, SA, WA, Vic
<i>Bubas bubalus</i>	Clay, loam, sandy loam	France	Releases currently underway in Australia
<i>Digitonthophagus gazella</i>	Clay, loam, sandy loam	South Africa	ACT, NSW, NT, QLD, SA, WA, Norfolk Islands. Did not establish in Tas; Predicted northerly distribution in NZ
<i>Euoniticellus fulvus</i>	Compact silty	France, Turkey	NSW, SA, Tas, Vic, WA
<i>Geotrupes spiniger</i>	Wet soils, clay, or silty	France	ACT, NSW, SA, Tas, Vic
<i>Copris hispanus</i>	Clay, loam, sandy loam	Spain	WA
<i>Copris lunaris</i>	Calcareous soils, sandy soils	Native to Europe including Spain, France and England	Not yet released in Australia
<i>Onitis alexis</i>	Clay, loam, sandy loam	South Africa	NSW, NT, QLD, SA, Vic, WA Did not establish in Tas; Predicted northerly distribution in NZ
<i>Onthophagus binodis</i>	Sandy loam;	South Africa	NSW, QLD, SA, Tas, Vic, WA, Norfolk Islands. Often in irrigated pastures
<i>Onthophagus taurus</i>	Clay, loam, sandy loam	Spain, Greece, Italy, Turkey	NSW, SA, Tas, Vic, WA
<i>Onthophagus vacca</i>	Heavy clay	France	Releases currently underway in Australia

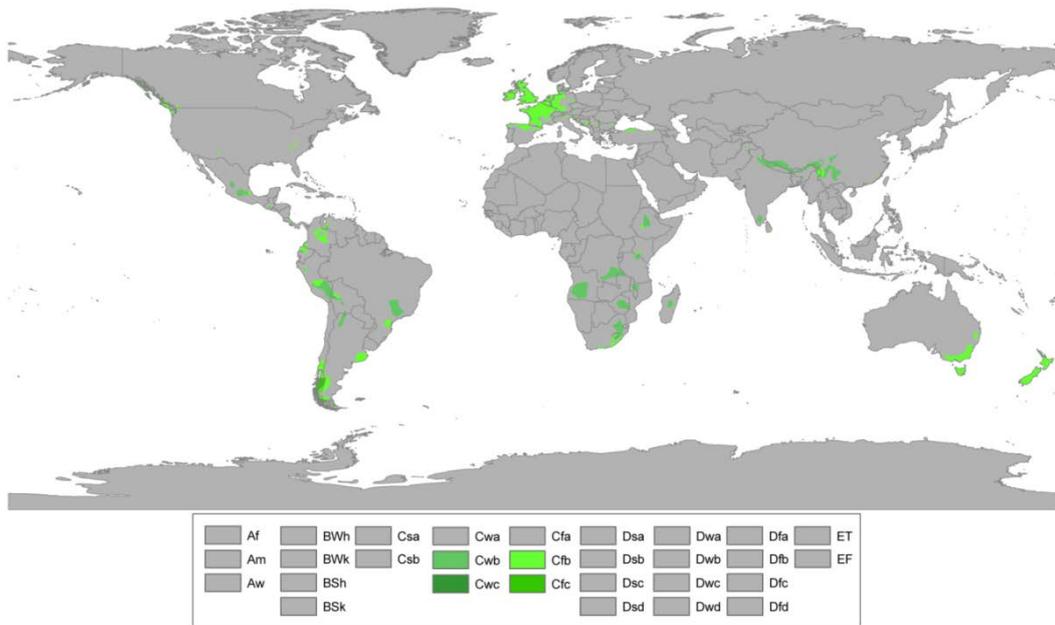


Figure 3. Global map of regions with Köppen climate groups Cfb, Cfc, Cwb and Cwc. Dung beetles that are native to regions that belong to the same climate group as New Zealand (mostly Cfb), should be adapted to the New Zealand climate.

https://en.wikipedia.org/wiki/Oceanic_climate#/media/File:Koppen_World_Map_Cfb_Cfc_Cwb_Cwc.png

4.1.3 Seasonality

Dung is produced all year round in New Zealand pastures, but the activity of each dung beetle species is seasonal, so a range of species is needed to ensure beetles are present on pastures all year. The range of species selected for release in New Zealand includes species that are predominantly active in all four seasons (Table 4). To ensure good dung removal, at least two dung beetle species (e.g. spring and summer active *O. taurus* and autumn and winter active *C. hispanus*) need to be established. The rapidity of dung removal can be further enhanced by selecting additional beetle species based on complementary daily activity pattern (i.e. diurnal, crepuscular or nocturnal).

Table 4. Activity of the novel dung beetle species (information from: Edwards et al. 2015). Crepuscular species are active at dusk and/or dawn

Species	Daily activity	Seasonal Activity
<i>Euoniticellus fulvus</i>	Diurnal	Spring to autumn
<i>Onthophagus taurus</i>	Diurnal	Spring to autumn
<i>Onthophagus vacca</i>	Diurnal	Spring to autumn
<i>Onthophagus binodis</i>	Diurnal	Late spring to autumn
<i>Geotrupes spiniger</i>	Crepuscular	Early spring to early winter
<i>Digitonthophagus gazella</i>	Crepuscular	Spring to autumn
<i>Onitis alexis</i>	Crepuscular	Spring to autumn
<i>Bubas bison</i>	Crepuscular	Mainly autumn to winter (but can continue to spring under suitable conditions)
<i>Copris lunaris</i>	Nocturnal	Spring to autumn
<i>Bubas bubalus</i>	Nocturnal	Late winter to summer
<i>Copris hispanus</i>	Nocturnal	Autumn to late spring

4.1.4 Summary

All beetles approved for release in New Zealand should be adapted to the Gisborne climate and all should be able to cope with the Gisborne soils. However, as beetle activity varies seasonally, a range of species will be required to maximise benefits.

Of the species that are currently available, several are active in spring and summer; *B. bison* is mainly active in autumn; and only *C. hispanus* is mainly active through the winter. A minimum of three species will therefore be required to ensure dung is removed from pasture year-round. Establishing more species may nevertheless be desirable as beetles can have complementary impacts on ecosystem services (Slade et al. 2017).

4.2 Assessment of potential risks, constraints and environmental benefits associated with dung beetle release by review of case studies of dung beetle releases elsewhere in New Zealand and overseas.

Dung beetle activity can lead to quite a diverse range of benefits including the removal of dung resulting in less area of fouled pasture, improvements to soils, reduced threats to animal and human health, and possibly reduced greenhouse gas emission from dung. Here we summarise research these benefits in Table 5 (column 2). For each broad category we also present the counter-balancing risks (Table 5, column 3), especially those that were considered during the release application process in New Zealand, including those raised by individuals or organisations opposing the releases. The mostly overseas research supporting this summary is presented in more detail in the following sections.

Table 5. Summary of the benefits and risks/constraints associated with the release of new species of dung beetles in New Zealand

Issue affected by dung beetles	Effects from dung beetle activities	Risks/constraints	Overall effect
Pasture fouling	Pasture fouling reduced by dung burial resulting in more pasture area available for stock grazing. National benefits to beef farming in New Zealand of NZ\$24–42 million.	No risks identified but one theoretical paper did rate benefits of “little consequence”.	Positive.
Soil attributes	Bioturbation from dung beetle burrowing increases aeration, reduces compaction, and increases depth of top soil.	The effects of dung beetles in soils of different types and in different climates is likely to be quite variable.	Positive but of variable magnitude.
Water infiltration and runoff	Increased soil permeability increasing water infiltration rates and reducing surface runoff.	Increased soil/nutrient losses in surface runoff due to soil excavation by dung beetles, but effects appear to be minor and short-term. Increased nutrient pollution through burrows creating preferential flow especially in “leaky soils” needs further research in NZ.	Positive overall, although more research is advised.
Soil nutrients/nutrient cycling	Increased nutrients, particularly N, enter soils with increased availability to plants. National benefits to beef farming in New Zealand of NZ\$45 million.	Effects on N cycle are complex with some studies showing increases in nitrous oxide gases lost from soil. One theoretical paper suggested benefits of increased nutrient cycling to Australian agriculture were likely to be minor.	Positive, but gaseous N fluxes needs further study.
Plant productivity	Increased.	Measured effect variable but none negative.	Positive in productive sector ecosystems.
Interactions with existing biota	Likely to increase earthworm abundance and activity. Unlikely to be many other benefits to indigenous fauna or flora.	Theoretical negative effects on earthworms very unlikely. No negative effects expected on indigenous dung beetles, rare chafer beetles, or any other indigenous fauna. Concerns that improved nutrient cycling could harm indigenous plants that are dependent on nutrient-poor soils (e.g. by encouraging weeds that thrive in nutrient enriched soils) are likely to be insignificant. This is because these environments do not have the consistently high amounts of fresh ruminant dung required to create dense populations of the new exotic dung beetle species.	Minimal interactions expected although synergy with earthworms (another “ecosystem engineer”) likely to be positive.
Human health	Benefits are likely from reduced pathogens in runoff to surface water, and reduced dung on pastures leading to less pathogen dispersal via flying animals (e.g. flies) or wind (dispersing dry dung/dust).	A risk of increased numbers of one pathogen (VTEC – <i>E. coli</i>) infiltrating into groundwater was considered to be limited to people drinking untreated water from vulnerable supplies (e.g. shallow bores). Over time, as deeper soils developed, this effect could reverse and become a benefit.	Positive.

Issue affected by dung beetles	Effects from dung beetle activities	Risks/constraints	Overall effect
Animal health: i) bovine Tb	Unlikely to be any benefits as epidemiology depends on occurrence in, and exposure to, reservoir hosts and/or direct transmission between cattle.	Risks raised were i) dung beetles themselves could be vectors of bovine Tb (by beetles being infected from the contaminated dung they utilise – either cattle or possum dung), and ii) dung beetles in NZ pastures could be an attractive food source for possums, the key reservoir host for bovine Tb in NZ, thus increasing the risk of transfer of bovine Tb to/from cattle and possums.	Risk was considered low based on overseas evidence, which was confirmed by further research in NZ commissioned by the Technical Advisory Group.
ii) Johne's Disease	Possible reduction in prevalence because there is less dung on the pasture surface (contamination of young cattle from fresh dung is thought to be the main transmission pathway between cattle).	Although the pathways for stock infection by Johne's Disease are not fully understood, and the causative agent can persist for long periods both in the environment and in wildlife hosts, the risk of dung beetles changing the epidemiology of this disease in NZ seems very low.	Minor positive effect (reduced disease incidence) or no effect.
iii) Gastrointestinal nematodes	Reduced numbers of infective 3 rd stage larvae in pasture foliage, and thus less infection of livestock, because dung is i) broken up (this desiccates 1 st +2 nd stage larvae); ii) processed into dung balls (this kills eggs and larvae); iii) buried by beetles (trapping larvae in soil).	Under warm moist conditions, aeration of fresh dung by beetles can lead to higher rates of hatching of nematode eggs. Shallow burial of dung by beetles could, in theory, allow greater survival of 1 st + 2 nd stage larvae through reduced desiccation. In moist conditions, and particularly in sandy soils, the developing 3 rd stage larvae could then migrate back up to the soil surface.	Overall effect likely to be positive, i.e. a substantial reduction in infection rates of livestock. However, under some particular combinations of environmental conditions, increased numbers of 3 rd stage larvae in pastures are possible. These sets of conditions are likely to be rare, but further research (including simulation modelling) is recommended.
iv) Parasite or disease transmission with dung beetles as intermediate hosts	Unlikely to be any benefits regarding the risk of animals becoming infected by parasites or diseases via intermediate hosts.	The new dung beetle species show strong preferences for the dung of large herbivorous mammals, so these beetles are highly unlikely to play any role in helminth transmission in New Zealand as intermediate hosts for carnivorous or omnivorous animals.	No effects.
Greenhouse gas emissions	Possibly some small reductions in CO ₂ equivalents in overall greenhouse gas emission (because of decreases in methane emissions from dung with beetle activity).	Results of studies are mixed and complex, typically with increases in emissions of nitrous oxides with dung beetle activity.	Overall, dung beetles may reduce emissions of greenhouse gases (as CO ₂ equivalents) but only by 0.05-0.13% of total emission from beef and milk production (because most emissions come from sources such as enteric fermentation which are unaffected by dung beetles).

4.2.1 Pasture fouling

Benefits

Rapid removal of dung from the surface of paddocks by dung beetles will reduce contamination of forage by livestock faeces, increasing the amount of forage available to grazing livestock. At any one time, up to 5% of cattle pastures might be excluded from grazing because it is covered by dung and/or in the pasture adjacent to dung pats that cattle avoid grazing in (Fincher 1981; Dymock 1993; Beynon et al. 2012). The activity of introduced dung beetles in New Zealand will result in more rapid removal of dung from the pasture surface than is achieved by existing species such as earthworms and small adventive dung beetles, which are relatively inefficient dung-buriers. Several studies have quantified the rate of dung removal from the pasture surface in the presence of dung beetles versus dung only treatments. In SE USA, Fincher et al. (1981) showed that dung beetles rapidly buried 78% of artificially applied dung pats. In Denmark, Holter (1979) showed increased levels of dung weight losses varying from 3 to 95% in studies over 3 years, with much lower dung losses in an unusually hot and dry year. Nervo et al. (2017), in a study in an alpine pasture in Italy, showed that the activity of tunnelling dung beetles led to 3.7 times faster weight loss from surface dung compared to a dung-only treatment. Also in Italy, Borghesio et al. (1999) showed much smaller effects on dung removal by beetles that varied from insignificant to about a 23% reduction in dung mass compared with the dung only treatment. However, dung beetles were rare at times during these trials and large tunnelling species were completely absent. In a study that combined data from a range of results from northern European research, Beynon et al. (2015) derived an overall figure of 45% for the increase in dung removal due to beetle activity in comparison to dung-only controls. In Canada, dung beetles removed 37% of the original fresh dung pat that had been added to pots in an experimental trial (Macqueen & Beirne 1975a). In Japan, dung beetle activity increased surface dung weight loss by 26–48% over a nearly 60-day trial period after the deposition of the artificial dung pats (Yamada et al. 2007). Beynon et al. (2012) show that losses in dung weight were greater with more species rich dung beetle communities compared with single species, and that the effects were particularly pronounced in treatments including disruption by ivermectin, a commonly used anthelmintic (i.e. the species rich dung beetle assemblages suffered less from the effects of ivermectin than species-poor assemblages).

The small, but widespread increases in pasture productivity because of reduced pasture fouling add up to substantial benefits on a national basis. For example, in the USA, Losey and Vaughan (2006) estimated that reductions in pasture fouling (i.e. increased available pasture area) because of dung beetle activity resulted in a national benefit of US\$122 million per annum to the beef industry. This analysis used only the 32 million cattle in the USA whose dung would be available to dung beetles; cattle not reared on pasture or that are treated with drenches that are harmful to dung beetles were excluded. The benefits in beef production were calculated pro-rata from the estimated 19% more pasture available for grazing as a result of dung burial by beetles (Losey & Vaughan 2006). In 2015 New Zealand had 3.5 million beef cattle (Stats NZ 2018), so annual benefits in 2015 to this sector alone could be around NZ\$24 million if the entire beef sector benefitted from dung beetles. This calculation was based on USA benefit figure, adjusted for the 3.5 million beef cattle in NZ in 2015 (Stats NZ 2018), annual inflation (3%) and exchange rate (0.72). In another similar study,

Beynon et al. (2015) calculated that dung beetle activity in the UK led to benefits from reduced pasture fouling (i.e. increased grazing) of UKP 6.2 per cow per year: this would be equivalent to an annual benefit to the beef cattle sector in New Zealand of NZ\$41.7 million. This calculation was based on UK benefit figure, given 3.5 million beef cattle in NZ in 2015 (Stats NZ 2018) and adjusted for exchange rate (0.52).

Risks/constraints

We identified no risks of harm from reducing pasture fouling. However, McKinney and Morley (1975) did use simulation models to suggest that rejection of fouled herbage around dung pats and the direct smothering of pasture growth by pats would be of little consequence for Australian pastures. This view has been challenged with the models called "simplistic" (Prestidge 1997), and with the comment that "today, not many farmers would agree". The recently re-invigorated Australian dung beetle research programme is intended to examine benefits of dung beetles on larger spatial and temporal scales (Department of Agriculture & Water Resources 2018).

4.2.2 Soil attributes

Benefits

Bioturbation is the displacement and mixing of sediments in soil, and is one of ecosystem services associated with tunneling dung beetles (Nichols et al. 2008). Only a few studies have measured the effects of bioturbation by dung beetles, but these show substantial benefits such as reductions in soil bulk density and increased soil aeration (Bang et al. 2005; Doube & Marshall 2014). These effects are likely to be particularly significant where soils are dry and hard (Doube & Marshall 2014) and presumably should help alleviate soil compaction caused by stock but until recently there have been no studies directly demonstrating this (Nichols et al. 2008). More recently, (Manning et al. 2016) used a penetrometer in field cages in Wales to measure soil compaction and showed a significant reduction of about 60% in surface hardness with one soil-ovipositing, non-burying dung beetle. Other species (including one very small dung-burying species) also showed reductions in surface hardness compared to a dung only treatment, but they were not statistically significantly different from the dung only treatment (Manning et al. 2016). In contrast, these authors failed to find any differences in soil bulk density as a result of dung beetle activity, but only shallow burying species were used in the experiment and the soils were not compacted to start with.

These changes to the physical structure of soils through the activities of dung beetles are also likely to contribute to improved pasture productivity (see Section 4.2.5 below) but no experimental studies have separated these effects from plant growth benefits from dung beetle activity improving nutrient cycling (Section 4.2.4) (Nichols et al. 2008).

Dung beetle activity has been reported to increase the depth of friable topsoil, mix subsoil with topsoil, and allow deeper root systems to develop (Doube & Marshall 2014). Burrowing by dung beetles could ameliorate some undesirable soil properties such as hydrophobicity in pumice soils, improve soil structure in some unusual soil types (e.g. Hawke's Bay soils with surface silica pans) and deep burrowing species may help disturb the firm layers/pans in soils (typically at 60 cm) (Jackie Aislabie, Manaaki Whenua – Landcare Research, pers. comm.)

Risks/constraints

The effects of dung beetle activity in different soils will be complex, and require further study particularly in the New Zealand context. There are also concerns about risks of rapid penetration e.g. of dairy effluent through “leaky soils” in New Zealand, and this is discussed further in Section 4.2.3 (Water infiltration/runoff) and under discussion of effects of dung beetles on human water supplies in Section 4.2.7 (Human health).

4.2.3 Water infiltration/runoff

Benefits

Bioturbation and tunneling by dung beetles combine to increase soil permeability to water. This can be shown directly by measuring water infiltration rates (Doube, 2005), soil water content (Johnson et al., 2016) or by showing reduced levels of water runoff as a result of dung beetle activity (Doube 2005; Brown et al. 2010). Doube (2005) reported in Australia that water infiltration rates into dry soils were 11× faster in a dung + beetle treatment compared with a dung-only treatment. In South Africa, infiltration rates were around 2× greater in dung + beetle treatment compared with a control with no dung (Brown et al. 2010). Improved infiltration rates are likely to be particularly beneficial in dry soils, helping to avoid runoff from summer rainfall or irrigation (Doube & Marshall 2014). In New South Wales, Johnson et al. (2016) showed that soil water content was around 10% higher in soils with dung and beetles compared with dung alone. Doube (2005) showed that, even when the soil had previously been saturated by heavy rain, runoff volume was reduced by 14% in dung + beetle treatments compared with a dung only treatment. Brown et al. (2010) showed runoff reductions of around 50–70% in a dung + beetle treatment compared with controls with no dung. Richardson and Richardson (2000) found an average increase in water infiltration rates of 129% when beetles + dung treatment was compared with no-dung.

Water runoff after simulated rainfall was recently study in New Zealand using the newly released dung beetle species. This study used small-scale cages and demonstrated reductions in mean runoff volumes from 49 to 81% as a result of dung beetle activity (Forgie et al. 2018). Overall, despite different methodologies in the various studies, there is clear evidence that dung beetle activity can substantially improve water infiltration rates into soil, lead to greater soil water content and reduce runoff.

Risks/constraints

There is a risk that dung beetle burying activities could lead to increased soil losses after rainfall. Indeed, Brown et al. (2010) measured higher inorganic soil losses in plots with dung + beetles versus controls with no dung when simulated rain was applied 2–3 days after dung deposition. Initially increased concentration of sediment in runoff is not surprising because the burying activity of dung beetles leaves small piles of loose soil on the pasture surface (J. Brown pers. comm.) A similar effect is reported with earthworms (Sharpley et al. 1979). With dung beetles this increase in sediment in runoff due to soil casts is temporary: Brown et al. (2010) found no effect of dung beetles when sediment loss was measured 6 months after the dung treatment was applied. In the New Zealand trials, Forgie et al. (2018) showed that amounts of sediment in the runoff were not increased with dung beetle activity under an

extreme rainfall simulation applied 2 weeks after dung deposition, but in a less-extreme rainfall simulation the presence of dung beetles actually resulted in a 97% reduction in mean sediment amount in runoff.

There is risk that runoff could contain nutrients and result in contamination of streams, rivers and lakes (PCE 2013). Very little research appears to have been done on the potential effects of dung beetles on nutrient content of runoff. However, Doube (2005) showed that dissolved organic carbon and dissolved nitrate were significantly lower in runoff from dung + beetle treatments after 3 months compared to dung-only treatments.

The risk of dung beetles increasing the amount of nitrate (or other nutrients) being leached down the soil profile was raised by Prestidge (1997). Deep burrowing dung beetles could create macropores, creating route for preferential flows (Tompkins et al. 2012), taking infiltrated water directly into groundwater (or into field drains if they are present). Analogous concerns have been raised over deep-burrowing, anecic earthworm species (Bardgett & Wardle 2010). Trials using large, deep soil cores (lysimeters) are planned for New Zealand and Australia to address this issue for deep-burrowing dung beetles, but preliminary results in New Zealand have been very encouraging with no elevated levels of C or N in leachate collected from the base of 600-mm-deep soil cores in a shallow fine sandy loam (over gravel) or an allophanic soil when dung + beetle treatments were compared with dung only treatments (Tompkins et al., 2012; Aislabie et al. 2016). Leaching through the soil profile could also be an issue with pathogens, and this is discussed in Sections 4.2.7 (Human health) and 4.2.8 (Animal health).

4.2.4 Soil nutrient levels/nutrient cycling

Benefits

Nitrogen

Several studies calculate the amount of nitrogen entering the soil based on the N content of the dung and the mass of dung being buried by beetles. Mittal (1993) calculated that dung beetles were burying 334 g/N/ha/day in India. In Australia, Gillard (1967) estimated that dung beetles had buried about 170 kg/ha of N in the 6 weeks following dung deposition on the grassland. In the USA, Fincher et al. (1981) estimated that dung beetles buried 175 kg N/ha.

However, these studies do not consider the possible complexities of N fluxes through the N cycle, which depend on how microbial activities are affected. The key processes are volatilisation (which releases ammonia gas, NH_3 , into the atmosphere), mineralisation (which makes nitrogen available for uptake by plants as ammonium, NH_4^+ , and then as the more important nitrates, NO_3^- , by nitrification), denitrification (loss of nitrous oxides to the atmosphere) and leaching (mostly NO_3^-) (Fig. 4) (Prestidge 1997; Nichols et al. 2008; Johnson et al. 2016).

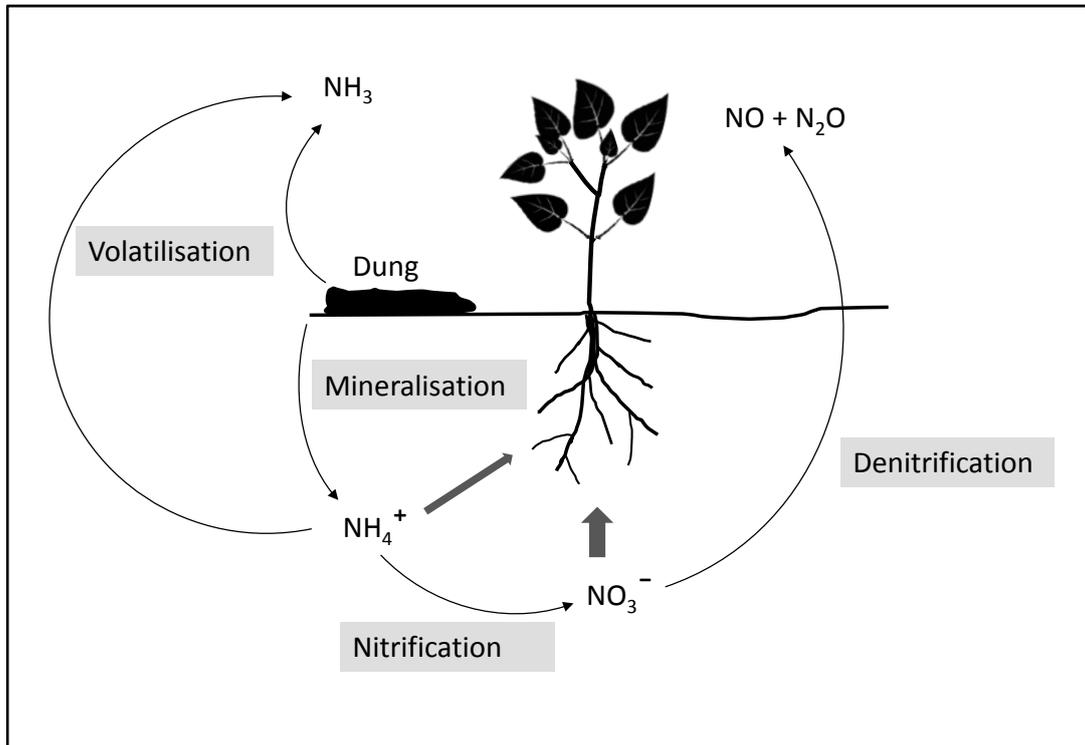


Figure 4. The nitrogen cycle, showing only pathways of most relevance to the impact of dung beetles. Plant uptake is shown by the broad arrows. Some other major pathways not shown are fixation of atmospheric nitrogen, temporary immobilisation of NH_4^+ and NO_3^- by microbial activity, and leaching (mostly of NO_3^-).

Mineralisation and nitrification are the processes whereby micro-organisms convert organic nitrogen into inorganic nitrogen (NH_4^+ and NO_3^-), which is then available for plants. Dung beetle activity has been shown to increase both mineralisation and/or nitrification (Yokoyama et al. 1991; Kazuhira et al. 1991a, 1991b; Lastro 2006; Yamada et al. 2007; Nervo et al. 2017). In Australia, Doube (2008) showed increases in nitrate of around 2.3× in treatments with dung + beetles compared with dung-only treatments using two soil types over 20 months following dung application. Similar results were obtained in another trial in South Australia (Doube & Dale 2012; Doube 2018). In Japan, Yamada et al. (2007) showed that dung beetle activity increased inorganic N in soils by up to 2.6× (7 days after dung deposition and beetle addition) compared with dung-only controls. Differences over the 56 days trial were not always as high as this day 7 peak, but even at the end of the trial inorganic N levels were 2.1× higher in the dung beetle treatments compared with the dung-only treatment (Yamada et al, 2007). In Indonesia, Shahabuddin et al. (2008) reported increases of soil N of 3.8% in dung + beetle treatments compared with dung only in a laboratory study. Overall, increases in mineralisation and nitrification should make more nitrogen available for plants, potentially increasing plant productivity (see Section 4.2.5). Gillard (1967) and Kazuhira et al. (1991b) showed that volatilisation (loss of NH_4^+ by release of ammonia gas), was reduced by dung beetle activity, which again has the potential to benefit plants. Several studies have shown that denitrification (the loss of NO and N_2O by microbial breakdown of NO_3^-) was by dung beetle activity (Slade et al. 2016; Piccini et al. 2017) but results were not always consistent (see Risks/constraints below).

Other nutrients

It is considered likely that other nutrients, e.g. P, S, K will be released in a similar way to N after dung beetle activity, although supporting data is lacking (Prestidge 1997). Yamada et al. (2007) showed that the effects of dung beetle activity on P and K in soils were not so clear as the consistent increases in N. In the USA, Bertone (2004) showed mostly increases in two primary nutrients (P, K), two secondary nutrients (Ca, Mg), and three micronutrients (Mn, Zn, Cu) in dung plus beetle treatments over a dung-only treatment in a pot experiment, but results were quite variable and few of the increases were statistically significant. Lastro (2006), in a laboratory study, showed some increases in soil K and P with dung beetle activity, but the results were quite variable. Doube (2018) showed mean levels of several important nutrients in subsoil were higher in dung plus beetle treatments versus dung only treatments in a trial in South Australia: phosphate (3.4× increase); organic carbon (1.4× increase); sulphur (1.6× increase); potassium (unchanged); iron (unchanged). These differences were measured over a period of 20 months following the one application of dung. Dung alone did not enhance nutrient levels in the subsoil compared with controls with no dung. Similar results were obtained in another trial in South Australia (Doube & Dale 2012; Doube 2018). Shahabuddin et al. (2008), in a laboratory study in Indonesia, reported increases of soil P of 25.8% and soil K of 53.9% in dung + beetle treatments compared with a dung-only treatment.

Economic value

Beynon et al. (2015) used an ecosystem services framework to estimate that dung beetle activity benefits the UK cattle industry by UKP 6.71 per cow per year through increased nutrient cycling. This was based on an overall average increase in inorganic N, P and K of 130% derived from a study in Japan (Yamada et al. 2007) and a study in the USA (Bertone 2004), and on the cost of providing these nutrients through fertiliser application (Beynon et al. 2015). For beef cattle in New Zealand this is equivalent to a total annual benefit of NZ\$45.2 million. This calculation was based on the UK benefit figure, given 3.5 million beef cattle in NZ in 2015 (Stats NZ 2018) and adjusted for exchange rate (0.52).

Risks/constraints

Results have not always been consistently beneficial. For example, Nervo et al. (2017) showed reduced levels of nitrification after one year in dung plus beetle treatments, and a few studies have shown that denitrification (loss of NO_3^- by the release of NO and N_2O) was similar or increased with dung beetles compared to dung-only controls (Yokoyama et al. 1991; Kazuhira et al. 1991b; Penttilä et al. 2013). As N_2O is a greenhouse gas this issue is discussed in more detail in Section 4.2.9 (Greenhouse gas emissions).

In one case, simulation models were used to suggest that the overall impact of dung beetle activity on nutrient cycling was unlikely to influence animal production in Australian pastures (McKinney & Morley 1975). However, this view has been challenged (Prestidge 1997) – see comments in Section 4.2.1 (Pasture fouling) – although it is a valid point that the potential benefits of dung beetles have been generally been extrapolated from results of small-scale experiments, often with enhanced beetle numbers in cages (McKinney & Morley 1975).

Finally, the risk assessment process undertaken as part of the application to release new species of dung beetles in New Zealand identified a possible risk of harmful effects in native plant communities through unwanted increases in nutrient cycling. In particular, the risk that processing and burial of dung from exotic grazing animals such as sheep, deer or horses in native grassland and subalpine shrublands might increase nutrient availability to plants and benefit exotic grasses that might then out-compete valued native plants (Landcare Research, unpublished information). This issue is discussed further in Section 4.2.6 (Interactions with existing biota).

4.2.5 Plant productivity

Benefits

Benefits from dung beetle activity in the above sections should result in greater pasture productivity in terms of increased biomass and/or pasture quality. Effectively, measuring pasture productivity responses to dung beetle activity is a bioassay that tests the combined effects of the biophysical benefits in the above sections (less pasture fouling, improved soil characteristics, better water infiltration/retention, and improved nutrient re-cycling).

Before the introduction of non-native dung beetle species in Australia, Bornemissza and Williams (1970) used a native, paracoprid species, *Onthophagus australis* Guerin-Meneville, in laboratory experiments and showed an increase of 81% in above-ground plant biomass when beetles were added to the dung at a density of 160 individuals/kg.

In field trials in the USA, using mesh fencing and treatments augmenting dung beetle numbers, Fincher et al. (1981) showed that rapid burial of dung by enhanced numbers of dung beetles resulted in yield increases of 22.4% in dry matter of Bermuda grass pasture, which were not significantly different from that achieved by chemical fertiliser (at a rate of 224 kg N/ha – which was the same total N/ha in the artificially applied dung). Also in the USA, Lastro (2006) reported grass yield increases of 50% in dung + beetle treatments compared with dung-only treatments in pot trials.

In South Korea, Bang et al. (2005) showed herbage grass yield was increased by dung + beetle treatments compared with dung only in field and pot experiments but differences (typically 5–13%) did not appear for 3–6 months. In a field experiment in Japan, Yamada et al. (2007) showed a significant increase of about 30% in herbage yield after 56 days comparing one of the dung + beetle treatments with the dung-only treatment in a 2001 trial; however, mostly there were no significant differences in herbage yield with the addition of dung beetles. Yamada et al. (2007) point out that their experiment involved a much lower rate of dung burial (equivalent to 93 KgN ha⁻¹) compared with the research by Fincher et al. (1981), which had a dung burial rate equivalent to 224 KgN ha⁻¹.

Several studies have been conducted in cooler, higher latitude or higher altitude regions. Borghesio et al. (1999) showed increases in primary production of up to 15% with dung beetles compared with a dung-only treatment in native heathland in northern Italy, but the effects were often lower or non-existent, probably because the study relied on natural colonization of the dung fauna and large dung beetles were not present at the site. Also in northern Italy, but at a higher altitude alpine site, Nervo et al. (2017) showed no effects of

dung beetle activity on plant productivity after 1 month but a 40% increase in plant above-ground biomass in treatments with a high species richness of tunnelers or dwellers after 1 year. Nervo et al. (2017) attribute the delayed responses in plant productivity to the oligotrophic nature of the alpine grassland in which the trial took place. In Canada, Macqueen and Beirne (1975b), using an experiment in pots, showed that crude protein levels in the grass increased by 12% in 1971 (not statistically significant) and 26% in 1972 (statistically significant) when comparing dung + beetles and dung-only treatments. These cooler climate results may be relevant to more southerly parts of New Zealand.

In a series of more recent field studies in Australia, using high densities of dung and dung beetles, Doube and Marshall (2014) showed improved pasture productivity of between 20-100% (in tonnes per ha) over durations of 2–9 years. It is uncertain how these dramatic figures can be extrapolated to larger scales but they at least indicate the upper bounds of potential benefits. Also in Australia, Johnson et al. (2016), in an experimental trial in pots, showed that the effects of dung beetle on plant productivity were strongly influenced by water supply: there were large increases in plant growth (e.g. biomass increased by ~3×) from dung beetle activity when plants were growing in drought conditions, but there were no significant differences in these plant growth parameters in either ambient or increased precipitation. The influence of very dry conditions may also explain the large effects of dung beetles on primary production shown for millet crops in a field trial in pots in Niger, although low-nutrient, sandy soils were probably also a factor leading to large effects: crop height at harvest was increased by 2×, and the dry weight of the ears by 10× (Rougon et al. 1988).

Dung beetle communities comprising 4 species, unperturbed by anthelmintic exposure, appeared to increase ryegrass biomass substantially (by about 30% compared with zero species controls) in pot experiments in the UK, although the effect was only marginally statistically significant (Manning et al. 2017). In an experiment in Finland, Slade and Roslin (2016) showed that plant biomass (wet weight) was higher by around 40% in soil from dung beetle treatments compared with soil from a dung-only treatment, but this effect disappeared where the treatments involved single species of dung beetles under simulated climate change (average 0.8°C temperature increase). The treatment with two species of dung beetles was unaffected by the simulated climate change, which Slade and Roslin (2016) suggest shows greater resilience to negative effects of climate change in multi-species dung beetle communities.

Risks/constraints

The magnitude of the increases in plant productivity in the above studies are variable depending on factors such as the study design, environmental variables, seasonal timing, and the dung beetle species involved. The same variables are likely to affect the impact of dung beetles in New Zealand. However, it is noteworthy that there are no cases of poorer plant performance from dung beetle activity compared with dung only controls, so there appears to be no risk of negative effects on plant productivity in agricultural systems from dung beetle activity. Concerns that increased plant productivity in some natural ecosystems where native plants are adapted to low soil nutrient levels might promote invasion of exotic weeds are addressed under Section 4.2.6 (Interactions with existing biota).

4.2.6 Interactions with existing biota

Benefits

Despite concerns that earthworms might be negatively affected by dung beetles (see Risks/constraints below), the evidence is that they actually benefit. For example, in Australia the burial of pastoral dung by beetles increases both the biomass of earthworms, and the depth at which earthworms were active (Doube & Marshall 2014). In the USA, Richardson and Richardson (2000) report 12–30 earthworms per cubic foot once dung beetles became common on their land, whereas they had been unable to find any earthworms in the previous 20 years when dung beetles were effectively excluded by extensive use of insecticides. In Brazil, Miranda et al. (1998) comment on the appearance of lumbricid earthworms in pots in their dung + beetle treatments in contrast with dung-only treatments where earthworms remained absent.

Risks/constraints

The introduction of new dung beetle species is intended to change the fate of dung deposited on pastures in New Zealand. If successful, then dung will be rapidly processed and buried, which is likely to make the dung less available for any existing species that are using the resource. Thus, introduced dung beetles could outcompete existing species that rely on this resource in New Zealand pastures.

Despite concerns that introduced dung beetle species would compete for dung resources with earthworms, and that reductions in earthworm numbers would have negative effects on soil quality (Nick Martin, Landcare Research, pers. comm.), the evidence is that dung beetle activity is beneficial to earthworms (see Benefits above).

During the release application process concerns were raised whether New Zealand's indigenous dung beetles might suffer negative effects from competition with the new species of dung beetles. This was discounted because all the indigenous dung beetles in New Zealand are forest specialists, whereas the introduced species are open habitat specialists. The introduced species may sporadically fly into relatively open forest remnants but only if there is fresh dung that is attractive to them. This is only likely to occur in damaged forest remnants that are being actively grazed by stock, and any biodiversity value of such forest remnants will reside in the mature trees. To restore such remnants, the obvious solution is to encourage the exclusion of stock by fencing, which will automatically reduce the likelihood of exotic dung beetles entering even open areas in the remnant. Over time, as an understorey develops, the remnant will become entirely unsuitable for the exotic dung beetles and might be colonized by the native dung beetles, although this could take a long time as all the indigenous dung beetle species are flightless.

Overall, no indigenous species in New Zealand are exclusively dependent on exotic ruminant dung as they have not evolved with this resource. One of the main insect groups exploiting ruminant dung in pastures are flies, which are discussed under Human Health (Section 4.2.7) and Animal Health (Section 4.2.8).

As dung is a continuously produced and abundant resource in pastures, the introduced dung beetle species will need to become widespread and consistently common to have a big impact on the recycling of dung. Also, dung beetles are recognized “ecosystem engineers”, particularly in the way they can affect soils, and these effects could have substantial effects on the existing biota in New Zealand where the exotic dung beetles become abundant. There is thus potential for dung beetles to have indirect effects on the existing fauna, for example by providing an additional food resource for predators that could have “knock-on” effects in food webs, or by other more subtle, indirect effects, e.g. by changing soil characteristics.

One potentially harmful indirect effect of introducing new species of dung beetles is whether they may increase nutrient levels in soils in habitats where this is undesirable. For example, there are extensively grazed areas like Central Otago, where rare endemic New Zealand plant species occur. If the soils in some of these areas become more nutrient-rich, then exotic plants such as grasses and shrubs will be likely to invade and outcompete the New Zealand endemics. Indeed, Nervo et al. (2017), in a nutrient poor grassland in Italy, show that dung beetle activity encourages the invasion of “mesotrophic” plant species (that prefer moderately raised soil nutrient levels) into experimental plots previously dominated by the “oligotrophic” plant species (that prefer very low soil nutrient levels). However, Nervo et al. used experimental mesocosms with dung and beetles added, so their result cannot simply be extrapolated to natural, unmanipulated systems. In New Zealand, grazed low-nutrient systems have extremely low stocking rates, and it seems highly unlikely that enough fresh dung would be produced to maintain large populations of introduced dung beetles. In fact, given the high altitude of many of these areas, they may not be colonized by the introduced dung beetles at all. Furthermore, dung beetles will not use the dry dung, which accumulates in some of these areas over years. The same arguments apply to feral grazers, such as deer and horses, which are maintained at low numbers.

Similar concerns have been raised for endangered fauna, such as the flightless *Prodontria* scarabs. However, the same arguments apply as above for rare plant species, i.e. we do not expect livestock stocking rates to be sufficient to create the consistently high populations of dung beetles required to ‘engineer’ the soil and thus affect the scarabs. Indeed, if stocking rates were high enough then the effect of dung beetles on the survival of the scarabs is likely to be of minor concern to the habitat changes that the stock would create. The rarest of these scarabs is *P. lewisi* Broun, restricted to a small reserve outside Cromwell (Barratt 2007): the only grazing animals of concern in this reserve are rabbits, and it is recognized that control of these is beneficial for conservation of the scarab. Rabbits do not produce a type of dung that the introduced dung beetles prefer, and species that do prefer rabbit dung such as the minotaur beetle, *Typhaeus typhoeus* (L.), were deliberately not selected for introduction.

Other indirect effects that were raised as concerns include predation of the new dung beetle species resulting in increased numbers of predator species, which could then impact on valued prey (invertebrates, birds, etc.) both in the pasture and perhaps in nearby habitats. This seems unlikely to be a serious risk because, if dung beetles are abundant enough to represent a new resource for predators then the dung will be being buried rapidly and then the beetles are in burrows, so out of reach to the types of predators present in New Zealand. Also, there is an existing dung-dwelling fauna of small beetles, fly larvae, etc. that already offers a resource to predators, so the risk pathway already exists. Indeed, the presence of new burying dung beetle species should mean that there is less dung on the pasture surface at

any given time, so the available resource to predators may actually decline. Any risks of indirect effects concerning disease transmission, e.g. of bovine Tb or Johne’s disease, are discussed in Section 4.2.8 (Animal health).

4.2.7 Human health

Benefits

In a risk assessment of the possible effects of releasing new exotic dung beetle species in New Zealand, Mackereth et al. (2013) identified four key pathways for human infection that that could be affected by dung beetle activities (Table 5): surface runoff; groundwater; flying animals; wind. They then broke each of these pathways down into three further categories for their risk assessment: numbers of pathogens at source; pathogen survival; human exposure to pathogens. The assessment focused on six enteric diseases that humans can contract after exposure to dung: cryptosporidiosis; VTEC infection (*E. coli*); campylobacteriosis; salmonellosis; giardiasis; yersiniosis. Surface runoff was considered the most important transport route of pathogens from dung to humans, and ESR considered that dung beetle activity should reduce this pathway across all three sub-categories (Table 5): i) burying dung reduces the opportunity for pathogens to pass from dung to surface runoff; ii) by breaking up and processing dung, beetles can reduce the survival of pathogens; iii) reduced pathogen loads in runoff will result in less exposure of human to these pathogens. The second most important transport route was considered to be via infiltration of pathogens into groundwater. This was considered to have some potential to increase risks of causing disease in humans (discussed under Risk/constraints below) but ESR did consider that dung beetle processing of buried dung would reduce pathogen survival in buried dung (Table 5). The last two, less important, pathways of possible disease transmission from dung to humans were (in decreasing order of importance) via flying animals and via wind. All the effects of dung beetles on these two pathways were considered to be positive, i.e. to reduce risk of disease transmission to humans from dung (Table 5). The overall effect of dung beetles was considered to be a decreased risk of humans contracting these six enteric diseases from dung (Table 5).

Table 6. The probable importance (1. Highest) of potential transport routes of pathogens from dung to humans – with the direction of effect that dung beetle activity is expected to have. Adapted from Mackereth et al. (2013)

Transport mechanism	Effect of dung beetles on pathogens:		
	Numbers at source	Survival	Exposure of humans
1. Runoff to surface water	Decrease	Decrease	Decrease
2. Infiltration to groundwater	Increase	Decrease	Increase
3. Via flying animals	Decrease	Decrease	Decrease
4. Via wind	Decrease	Decrease	Decrease
Overall	Decrease	Decrease	Decrease

Flies visit animal faeces and can transfer pathogens to human food or directly to humans. The three most significant fly species in New Zealand that could be affected by dung beetles are the striped dung fly (*Oxysarcodexia varia* (Walker), which breeds in cow and sheep dung; the false stable fly (*Muscina stabulans* Fallén), which also commonly inhabits dung; the house fly (*Musca domestica* L.), which largely breeds in decaying organic matter but does breed in horse dung. The burial of dung will decrease the transport of pathogens by flies, although it is unlikely to have much effect on fly numbers (other than perhaps the striped dung fly).

Risks/constraints

ESR considered that one of the six pathogens they assessed (verotoxigenic *Escherichia coli*; VTEC; a highly labile microbe expected to be influenced by any changes in microbial-bypass-flow process in soil) might have an increased risk of infecting humans via groundwater (Table 5). ESR present reasons for discounting the other five pathogens via this route, such as: direct destruction by dung beetles; high infectious dose needed; low pathogen survival rates in soil; large size – for *Giardia*. In contrast, VTEC could increase in groundwater because it is present in large quantities in ruminant dung, it survives well in the environment, and has a relatively low infectious dose. However, over time, as the activities of dung beetles result in deeper soils, ESR note that the risk of VTEC infecting humans via groundwater may reverse. They also point out that the risk to people of increased exposure to VTEC in groundwater would be constrained to people drinking untreated water from vulnerable supplies (e.g. shallow bores) close to pastures.

ESR did consider that *Giardia* and VTEC were present in dung at high enough concentrations that a single dung beetle might be able to carry an infectious dose for a human. So, for example, there would be a risk of infection if a child swallowed a dung beetle. However, ESR point out that there is no evidence from areas with abundant dung beetles in Australia, the USA or elsewhere, that children swallow dung beetles, and that risks of children contacting ruminant dung directly will reduce if dung beetles become abundant. During the release application process, a risk was repeatedly raised that swarms of night-flying dung beetles could be attracted to light in peri-urban areas and come into contact with immunologically naïve people. ESR considered that this risk was not based on any observations of this occurring in other areas in the world where dung beetles are common. Furthermore, in New Zealand there is no “smoking gun” of peaks in VTEC or other diseases that could be transported from dung to people in Northland and Auckland where the Mexican dung beetle is common. Indeed, the trend is for lower disease occurrences in these areas compared with areas with no burying dung beetle species such as South Canterbury, Otago and Southland. However, ESR considered that, accompanying the introduction, it would be useful to:

- examine the number of pathogens in unburied dung pats, buried dung, emerging dung beetles and adult dung beetles;
- quantify the number of pathogens in water and the quality of water from water sources in some locations before and after dung beetle introduction.

Some recent research has been done on the effect of dung beetles on pathogens in water leaching through soil columns using soil cores in undisturbed barrel lysimeters. Testing the leachate for the indicator microbe *E. coli* showed no pattern of greater microbial loading in the leachate from the soil cores with dung beetles and dung compared to dung only. The

trials used both soil cores from the MacKenzie Basin (shallow fine sandy loam with 300 mm of fines over gravels) and an allophanic soil from near Hamilton (Tompkins et al. 2012; Aislabie et al. 2016).

4.2.8 Animal health

Bovine TB

Bovine tuberculosis (TB) is an infectious disease caused by the bacterium *Mycobacterium bovis*, and is one of the world's most serious animal health problems (TBfree 2012). In New Zealand, cattle and deer are the species most at risk of contracting the disease, but the main reservoir host is the possum (Nugent 2011; Livingstone et al. 2015). TBfree is a nationwide programme of livestock testing and pest control that exists to eliminate the disease from livestock by 2026, from possums by 2040 and from New Zealand by 2055 (TBfree 2012). Benefits

As transmission of bovine TB occurs largely by oral or respiratory routes, and its epidemiology in New Zealand is largely driven by the presence of the disease in the key reservoir host, the non-native brushtail possum (Nugent 2011; Livingstone et al. 2015), the addition of new species of dung beetles is very unlikely to result in any benefits in terms of reducing risks of bovine TB infection in livestock.

Risks/constraints

Landcare Research conducted several studies to improve our knowledge in regard to two perceived disease risks (Tompkins et al. 2012; Forgie et al. 2014). These studies addressed two key questions: (1) that contaminated dung beetles may potentially transport *Mycobacterium bovis* (the causative agent of bovine TB) away from either cattle or possum dung; (2) dung beetles on pasture could be a food source for possums or encourage their bush-to-pasture movements and, potentially increase rates of TB transmission between wildlife and cattle.

- 1 To understand the risk of dung beetles disseminating *M. bovis* away from either cattle or possum dung, two key components were investigated: i) first whether TB-infected cattle produce *M. bovis*-contaminated dung to which dung beetles could be exposed; and ii) whether dung beetles utilise possum dung (the possum being the primary wildlife host of Tb in New Zealand). First, dung samples collected from 12 tuberculous cattle (at least three of which had sufficiently generalised TB for their carcass to be condemned) failed to yield any positives upon gold-standard bacteriological culture for *M. bovis*. Second, no-choice host range tests showed that possum dung is rarely explored, let alone used, by dung beetles. We concluded that there is a negligible current risk of dung beetles acting as Tb transport hosts in New Zealand.
- 2 To understand the risk of possums increasing their bush-to-pasture movements, captive feeding trials with nine possums were first used to investigate whether they would forage for and eat dung beetles. With all of the dung beetles included in cages with possums being accounted for after 2 days' exposure, and no evidence of any possum foraging for the beetles, these trials demonstrated that possums are unlikely to forage for and eat dung beetles. To further understand this risk, a diet survey of free-living

possums in an area of high dung beetle availability in Northland was carried out. No dung beetle remains were found in the stomach of any of 30 possums examined. With the possums clearly foraging on pasture (evident from high stomach grass contents), it was concluded that there was negligible risk of altering possum foraging behaviour and hence negligible risk of additional dung beetle species potentially increasing rates of TB transmission between wildlife and cattle.

Johne's Disease

The following information is extracted from publications and the website Johne's Advisory Group (JAG, 2018). Johne's Disease, caused by bacteria (*Mycobacterium avium* subspecies *paratuberculosis* – or MAP for short), is an autoimmune reaction that develops in response to the MAP infection. The intestinal wall of the animal thickens as the immune system attempts to seal off the invading bacteria that it cannot eliminate, resulting in the animal's decreased ability to absorb nutrients from the diet. It is a very close relative of the bacteria that cause tuberculosis in cattle (*M. bovis*). Today, Johne's Disease is a significant animal health issue worldwide in developed livestock industries, particularly in dairy, but also in sheep and deer. The causative agent, MAP, can be found in the environment, surviving up to 18 months, and is also occasionally found in some species of wildlife. Johne's Disease is common on New Zealand dairy farms but few animals show clinical symptoms. The disease costs the dairy industry in New Zealand between \$40 million and \$90 million every year in lost milk production and poor calving rates. While animals are typically infected at birth by contact with faeces from infected adult animals, the onset of clinical disease is not immediate. In deer, clinical symptoms are normally seen in yearlings and weaners. In sheep and cattle, the infected animals are normally between 2 and 6 years of age. Stressful situations can trigger clinical disease in infected animals.

Benefits

By removing dung from the surface of pastures, dung beetles may reduce the opportunity of MAP to spread from contaminated faeces to infect other stock on the pasture or wildlife, but the effect is likely to be minor given that most stock are thought to be infected at birth (JAG, 2018).

Risks/constraints

Risks considered were: i) will burying dung increase the environmental load of MAP because MAP left on the surface in dung will be killed by desiccation or exposure to UV; and ii) will MAP be spread through dung beetles being predated in dung pats or after dispersing from dung pats, potentially increasing the environmental prevalence of MAP in wildlife.

To understand the risk of dung beetle activity increasing microbial percolation through soil, two leaching experiments with soil cores in lysimeters were conducted. Testing the leachate for the indicator microbe *Escherichia coli* (a highly labile microbe expected to be influenced by any changes in microbial-bypass-flow process in soil) showed no pattern of greater microbial loading in the leachate from the soil cores containing dung and dung beetles compared to dung alone). The studies concluded that the risk is negligible of dung beetles

increasing freshwater microbiological loading, including MAP, via increased groundwater contamination (Tompkins et al. 2012; Aislabie et al. 2016)

As dung and its associated fauna already represent a resource for predators, a pathway for wildlife to contact MAP via ruminant faeces already exists (Nugent et al. 2011). As the new dung beetle species are dung-buriers, when they are active, there will be less dung available on the surface of pastures for predators to forage in. If anything, dung beetles will reduce the exposure of wildlife to dung via this pathway. It is possible that mustelids, rodents, birds, cats, possums, and pigs could occasionally eat a dung beetle but for infection to occur the beetle would have to be contaminated with MAP, and MAP would need to be present in sufficient quantity to be an infective dose to the mammal eating the dung beetle. Given that burying dung beetles spend most of their lifecycle underground, we considered there was a very low risk of the new species increasing the spread of MAP to wildlife above the current rates of spread and incidence (Nugent et al. 2011).

Gastrointestinal nematodes

As in Australia, concerns were raised in NZ that the survival of gastrointestinal nematodes of stock could be enhanced in dung that was disturbed and buried by dung beetles, and that later migration to the surface of the infective 3rd stage larvae (L₃) could lead to greater infection rates of stock (Hughes et al. 1975). In response, Manaaki Whenua undertook a detailed review of the possible effect of dung beetles on gastrointestinal nematodes of stock (Fowler 2013), which is summarised here.

Benefits

Most studies comparing dung in the presence or absence of dung beetles reported substantial reductions in the number of infective third stage larvae of gastrointestinal nematodes at the soil surface or on pasture foliage. Three mechanisms contribute to this reduction: i) the break-up of dung on the surface by dung beetles often results in the dung desiccating faster than it does in an undisturbed pat, and can result in death of the desiccation-intolerant 1st and 2nd stage nematode larvae; ii) burial of dung by dung beetles appeared to destroy a high proportion of nematodes, presumably by the processing of dung by the adult beetles; iii) unless burial is very shallow (<10 cm), buried 3rd stage nematode larvae are usually unable to migrate back to the pasture surface and will eventually die.

Risks/constraints

The greater access to oxygen in dung that beetles have broken-up can lead to a higher proportion of nematode eggs hatching compared with dung not exposed to beetles, because the anaerobic conditions inside the undisturbed pat inhibit the hatching of nematode eggs. Some studies have shown greater numbers of 1st- and 2nd-stage nematode larvae in dung disturbed by dung beetles, particularly dung-dwellers that do not bury dung. However, this requires the dung to remain moist so that the 1st- and 2nd-stage larvae do not desiccate. A concern was raised both in Australia and New Zealand that buried dung might provide a good, desiccation-free environment, allowing high numbers of nematodes to reach the infective 3rd stage of larval development. Given moist enough conditions, 3rd-stage nematode

larvae are capable of migrating back to the surface from dung buried to 10 cm or sometimes deeper, and experiments where dung was buried near artificial barriers often reported larval migration from depths of 15–20 cm. However, the barriers may be providing continuous films of moisture that encourage larval migration so these results need to be interpreted with caution. The concern then was that burial of dung by dung beetles could enhance survival of nematode larvae and later migration of infective 3rd-stage larvae to the surface could increase infection of grazing stock compared with dung remaining intact on the surface. This so-called 'time-bomb' effect was, however, not supported by most studies.

One issue is that many field studies of the effect of dung beetle activities were conducted in warm, tropical environments, so these may not necessarily be relevant to cooler climates. Other trials were laboratory based and were operated at temperatures that were more akin to a warm temperate summer. A few dung burial trials were conducted outside in cool temperate areas, but none used dung beetles. Overall, the effects of climate on the interaction between dung beetles, gastrointestinal nematodes, and stock re-infection rates are complex, and some further studies in cool temperate areas would be useful. A recent study in New Zealand showed mostly reduced levels of infective 3rd-stage larvae of one gastrointestinal nematode species as a result of dung beetle activity (Forgie et al. 2018).

Beynon et al. (2015) used an ecosystem services framework to estimate that dung beetle activity benefits the UK cattle industry by UKP19.96 per cow per year through decreased incidence of gastrointestinal nematodes (and resulting increases in weight gains of beef cattle). For beef cattle in New Zealand this is equivalent to a total annual benefit of NZ\$134 million. This calculation was based on the UK benefit figure, given 3.5 million beef cattle in NZ in 2015 (Stats NZ 2018) and adjusted for exchange rate (0.52). An important constraint on these benefits being achieved is that farmers use dung-beetle-friendly drenching chemicals and/or drenching practices (see Section 4.6).

Dung beetles as intermediate hosts for diseases/parasites

Some parasites and diseases have indirect transmission pathways where an intermediate host carries the pathogen and can pass it on when it is eaten by the main (definitive) host (Nichols et al. 2017). Examples with dung beetles include several parasitic helminths and diseases such as *Toxoplasma gondii*, a globally widespread disease of cats (Nichols et al. 2017).

Benefits

The introduction of new dung beetle species into New Zealand is unlikely to provide any benefits regarding the risk of animals becoming infected by parasites or diseases via intermediate hosts.

Risks/constraints

One experimental study has shown that dung beetles that had been in contact with cat faeces contained viable oocytes of *T. gondii*, and that when these dung beetles were fed to mice, and the mice then fed to cats, infection of the cats could occur (Saitoh & Itagak, 1990). However, the importance of this transmission pathway in real situations is unknown, and *T. gondii* is frequently transmitted by direct contact with cat faeces or by contamination of food,

soil, etc. (Pereira et al. 2010). The new species of dung beetles released in New Zealand do not utilize cat faeces (see Table 1, Section 4.2) and so the transmission pathway via dung beetles is unlikely to be of any significance here.

Dung beetles have been reported as intermediate hosts for several parasitic helminth worms (Nichols et al. 2017). However, for dung beetles to become significant intermediate hosts they need to associate with the faeces of the definitive host, which must always be a carnivore or omnivore that feeds on the beetles directly, or consumes another intermediate host that has fed on a dung beetle. The new dung beetle species show strong preferences for the dung of large herbivorous mammals (Table 1, Section 4.2), so these beetles are highly unlikely to play any role in helminth transmission in New Zealand.

4.2.9 Greenhouse gas emissions

Farming is a major source of greenhouse gases (Piccini et al. 2017) and contributes about a half of New Zealand's total emissions (Pinares-Patiño et al. 2009). Recent studies with dung beetles have yielded some mixed and complex results

Benefits

Penttilä et al. (2013) showed that mostly dung-dwelling dung beetles in Finland reduce methane (CH₄) emissions from dung pats, but that the greenhouse gas effects of these were dwarfed by the amounts of CO₂ being released from pats. Overall, when calculated as CO₂ equivalents (CO₂e), there was a 0.6% reduction in greenhouse gases in the presence of beetles versus dung alone (Penttilä et al. 2013).

Piccini et al. (2017), in a laboratory experiment in Italy, showed an overall decrease in CO₂e in the presence of dung beetles of 21.3% compared with dung alone, but the only dung beetle treatment that was statistically significant alone was the most species-rich treatment (3 species). The reductions in CO₂e were due almost entirely to a reduction in N₂O emissions in the presence of the three beetle species (Piccini et al. 2017).

In Japan, Iwasa et al. (2015), in a laboratory study, showed that the presence of dung beetles compared with dung only decreased CH₄ emissions by 42%, but emissions were dominated by an increase in as CO₂ (see under Risks/constraints below).

Slade et al. (2016) took a broader view of greenhouse gas emission from dung with or without dung beetles, showing that relative to the total lifecycle of meat and milk production the decrease in total CO₂e emissions by the action of dung beetles in Finland was likely to be only 0.05–0.13%. This low figure is in part due not only to the large amount of livestock greenhouse gas emission originating from enteric fermentation leading to oral emissions, but also to the typically 250 days/year that cattle in Finland are not on pasture (Slade et al. 2016). Slade et al. (2016) do note that the contribution of dung beetles to reducing greenhouse gas emissions from cattle farming will be greater in systems where livestock spend larger parts of the year on pasture (as in New Zealand) and with larger and more diverse dung beetle faunas (as New Zealand is trying to create). Overall, dung beetles appear to offer some small levels of mitigation of greenhouse gas emission from agriculture, but further research is needed in a range of livestock systems and climates.

Risks/constraints

Penttilä et al. (2013) showed that mostly dung-dwelling dung beetles in Finland increase nitrous oxide (N₂O) emissions but in terms of CO₂e there was a 0.6% reduction in greenhouse gases in the presence of beetles versus dung alone (see Benefits above).

Piccini et al. (2017) showed that the large burrowing dung beetle, *Copris lunaris*, created a small peak in CH₄ emission that the authors attribute to the large brood balls of this species creating more anaerobic conditions than in the smaller brood balls of the other dung beetle species. However, CH₄ emissions were much lower than N₂O or CO₂, and overall there was a decrease in CO₂e emissions in these trials (Piccini et al. 2017) (see Benefits above).

In Japan, Iwasa et al. (2015), in a laboratory study, showed that the presence of dung beetles compared to dung only increased CO₂ emissions by 3.7× and increased N₂O emissions by 1.2×. Interpretation of the CO₂ emissions increase was complicated by the large numbers of beetles (30) confined in a 16-cm-diameter glass experimental chamber because the authors observed beetles frequently flying to try to escape from the container: such high activity levels will have been generating CO₂ from respiration in a way that would not occur in the field (Iwasa et al., 2015).

4.3 Evaluation of the environmental benefits to waterways of releasing dung beetles in the Wharekopae, Motu, and Waiapu catchments

Almost all experimental studies of dung beetle environmental benefits have relied on laboratory or field mesocosm studies (i.e. moderately small cage/enclosure studies). There have been very few experimental studies at scales approaching paddock level although research studies led by Fincher in the USA and Doube in Australia are at larger scales than most (Fincher 1981; Doube & Marshall 2014). No experimental studies have been conducted at farm- or catchment-level scales. The only catchment-scale study of possible benefits from dung beetles of which we are aware is the modelling of bacterial pollution of waterways by Dymond et al. (2016), and the dung beetle input to this model was based on only estimated parameters. Dymond et al. (2016) assumed that dung beetles would remove all dung and establish on 70% of farms. Dung beetles are unlikely to remove all dung in all environments at all times of year. We do not yet know what level of dung removal will be achieved by the suite of dung beetles approved for release in NZ, and where the gaps will be. We need to collect data before we can make realistic catchment level predictions. We now have some preliminary data on the effect of dung beetles on water runoff, and while these data suggest that by reducing runoff, the impact of dung beetles on overland flow of faecal material may be greater than Dymond et al. (2016) estimated (Forgie et al. 2018), much more research is needed, and some possible types of studies are suggested below.

There are logistic reasons why mesocosms have been favoured: it is impracticable to manipulate dung beetle numbers at larger scales, particularly in environments where dung beetles are already present. We do note here that future research in New Zealand offers an opportunity to manipulate dung beetle numbers on larger spatial scales than had been attempted to date, as there are large areas of New Zealand that completely lack significant burying species of dung beetles. Nevertheless, cost is also a constraint, with large-scale manipulation experiments, and there is also the risk that dung beetle migration could nullify

the applied treatment differences before enough time had elapsed to detect the large-scale effects of the beetles.

An ideal combination of future studies might be:

- 1 mesocosm experiments to align studies to previous work and allow detailed manipulation experiments and measurements;
- 2 larger scales might be feasible (paddock level, or even farm level, depending on replication level, ability to apply treatments, and resources available). There would have to be some very careful consideration of experimental siting, design and sampling. Confounding factors such as different fertiliser application, nutrient management, other mitigation systems (e.g. riparian fencing/plantings), will represent major problems for data analysis and interpretation of the results (and, where possible, need to be thought through in advance in the experimental design). Linkage to the mesocosm experiments would be vital;
- 3 Catchment level studies. These would have to rely on well-parameterised modelling studies (with parameters estimation emerging from 1/ and 2/). Comparative experimental studies at catchment levels are simply impossible for logistic and economic reasons, even though, in theory, they could seem feasible in NZ;

Some studies overseas have used differences in applied levels of harmful drenches as a way to manipulate dung beetle assemblages, but these chemicals are likely to be affecting other components of the systems as well, particularly other insects, earthworms. etc. However, once dung beetles became common in a catchment, then farms that were unwilling to alter dung-beetle harmful drench regimes could act as farm-level control sites.

One farm in one of these catchments could be considered as a sampling site under the Australian dung beetle programme that has just started. The resources for monitoring this site would be covered under the new programme, and it could be a good way to up-skill GDC staff and farmers into small scale evaluation methods.

4.4 Assessment of two privately-funded releases that have occurred in the district

4.4.1 Site 1: Rata Hills, 755 Oliver Road, RD 1, Matawai 4075

29/2/16: whole farm pack comprising 200–500 of each of *G. spiniger*, *Onthophagus taurus*, *O. binodis*, *Copris incertus*) released in Feb/Mar 2016 plus a late season pack of 200–500 *O. binodis* released in April 2018.

The release site for *G. spiniger* and *C. incertus* was not ideal, being in a high, windswept wind tunnel area centrally located on the farm. In addition, the paddocks were very large, and had low densities of stock faeces. It is likely that the beetles would have dispersed, with wind assist, downhill into leeward paddocks if they have established. *Onthophagus binodis* and *O. taurus* were released in a low-lying sheltered area, and their prospects for establishment are very good. Unfortunately, *O. binodis* and *O. taurus* were overwintering at the time of this

survey so their establishment could not be assessed. No beetles or beetle signs were found at this site.

4.4.2 Site 2: Anne Sparks, 1284 Kanakanaia Road, Te Karaka 4091

1/12/15: farm starter colony of *G. spiniger* (approximately 250 beetles). This 20-ha site was considered optimal for beetle establishment being sheltered between high hills, with ample dung being produced across the site. However, the small starter release of *G. spiniger* was split up and released at dispersed locations across the farm. This dispersion of the already small release is likely to have reduced the chance of the beetles establishing a viable breeding population. In addition, during this visit large numbers of magpies were noticed, and these are known predators of dung beetles, so predation may have further reduced the chance of these releases establishing. No beetles were found and no signs were seen of their activity (soil casts or disturbed dung).

Unfortunately, the weather in the region had been cold and wet for a couple of weeks before the assessment visit. Beetles in these conditions are inactive, which limits any fresh signs of activity.

It is not unusual for initial assessments of establishment of dung beetles (or other biocontrol agents) to be negative. Dung beetle numbers can take several years to build up to levels where detection on one brief visit is likely. More intensive monitoring, such as the use of baited pitfall traps, may be more successful but requires more effort. A visit earlier in the season would be more likely to detect signs of reproductive activity such as burrowing, which leaves soil casts.

4.5 A workshop (to be held in Gisborne) to provide guidance for exemplar farmers in the three catchments (who have expressed interest in dung beetle releases on their properties)

Dr Shaun Forgie ran a workshop in May 2018 with Gisborne District Council. Attendance was disappointingly low at five. The workshop covered the need to focus on the relatively easily and cost-effectively assessed *E. coli* as the indicator for water quality (Dymond et al. 2016; McDowell et al. 2017; Forgie et al. 2018). Catchment-level initiatives were discussed with the possibility of GDC subsidising farmers. GDC is looking to deploy beetles in two catchments if they can get the farmers to buy in. The dung beetle species that were most likely to be used in the area, and the numbers needed for release, were discussed. Future workshops will be useful to train farmers in simple monitoring techniques to assess the numbers and impact that dung beetles are having on their pastures.

4.6 Advice and recommendations to GDC on the best and most cost-effective ways of implementing dung beetle releases within the three catchments

4.6.1 Best implementation methods

DBI has good advice for farmers on their website and bring in that it is currently the only supplier and can work with the council to provide recommendation on best dung beetles for

target area. The selection of dung beetle species should be guided by the preferences of the species for soil type, dung/stock type and climate (Section 4.1).

To encourage the development of large populations of dung beetles, farmers will need to:

- 1 ensure their farms are “dung beetle friendly” e.g. reduce the frequency of drenching, avoid chemicals that do most harm to beetles, and try to focus drenching on target at-risk groups of stock
- 2 consider using a quarantine pasture for the treated livestock group which is downwind and/or some distance from the dung beetle release site: this way dung beetles are less likely to be exposed to harmful drench chemicals
- 3 consider cross/rotational grazing to reduce pasture contamination by infective stages of gut parasites.

4.6.2 Cost effectiveness

Gisborne District Council should try to get farmers in the three catchments interested in purchasing release packages of dung beetles. It may be helpful to kick-start this process by the council funding some releases to set up a demonstration farm. This farm could be selected to have environments where dung beetle establishment is likely to be rapid (see advice in Section 4.1). It is important that the farm is dung-beetle friendly (see above). If visiting farmers see success it should encourage further investment in releases.

Eventually many populations of dung beetles would be self-sustaining, although in some areas seasonal “re-seeding” with dung beetle releases might be necessary. In some cases, local numbers of dung beetles would become sufficiently high for collection and re-distribution to take place. Initially, such activities could take place at council-organised field days/workshops.

5 Recommendations

- Releases of dung beetles should be matched to the environments they are intended to operate in, although, given the restricted range of species currently available in New Zealand, there are limitations.
- GDC can use benefits/risks to support investment in dung beetles and answer any public concerns over the release of new species of dung beetles in the region.
- GDC should engage with ongoing dung beetle research to facilitate monitoring at mesocosm, paddock, farm and/or catchment levels.
- GDC can use this report to provide guidance to farmers on the best and most cost-effective ways to obtain benefits from dung beetles across the three catchments.
- One farm could be considered as a sampling site under the Australian dung beetle programme, which has just started. The resources for monitoring this site would be covered under the new programme, and it could be a good way to up-skill GDC staff and farmers into small scale evaluation methods.

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