A Nuffield Farming Scholarships Trust Report

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Riding the Slime Wave: Gathering Global Data on Slug Control

Dr Jenna Ross

August 2019

NUFFIELD UK

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A Nuffield (UK) Farming Scholarships Trust Report

Date of report: August 2019

"Leading positive change in agriculture. Inspiring passion and potential in people."

Title	Riding the Slime Wave: Gathering Global Data on Slug Control
Scholar	Dr Jenna Ross
Sponsor	Royal Highland and Agricultural Society of Scotland (RHASS) and the Agricultural and Horticultural Development Board (AHDB) Cereals and Oilseeds
Objectives of Study Tour	• Characterise the key slug species in the UK • Identify potential slug invasions and their impact on biosecurity • Determine direct and indirect economic risk of slugs • Review slug monitoring systems • Evaluate slug control options • Determine the future of malacology • Investigate novel commercial opportunities for the utilisation of slugs
Countries Visited	Australia, Belgium, Brazil, Canada, Japan, Kenya, New Zealand, Norway, United Kingdom, South Africa and Spain
Messages	• Over 50% of slug species in the UK are exotic, so it is imperative that biosecurity protocols are developed to prevent further slug invasions • Slugs have a direct economic impact on crop damage, as well as an indirect impact on human and animal health, rejection of exported crops due to contamination and impact on soil health (through slug control strategies) • There is a drive to incorporate technology into slug monitoring systems • With uncertainty over metaldehyde, Iron (Ferric) phosphate may be the only 'chemical' control option available in the future • The use of nematode bio-molluscicides is currently not feasible in broadacre crops due to cost, volume of water required, storage and shelf life • Agronomic and cultural practices are playing an increasing role in controlling slugs, with a surge in farmer led research in this area • Farmers should consider a slug IPM strategy pyramid, tailor-made to each field • The study of malacology appears to be in difficulty, with no clear succession plan in place, and limited funding to share and develop ideas • Perhaps we are missing an opportunity and we should be farming slugs instead, targeting slugs and their bi-products towards the food, cosmetic and pharmaceutical industries

EXECUTIVE SUMMARY

Slugs are one of the top agricultural and horticultural pests in the UK. Current methods for control rely on molluscicide pellets containing either metaldehyde or Iron (Ferric) phosphate. In December 2018, Defra made the decision to ban the outdoor use of metaldehyde due to its impact on birds and small mammals, but in July 2019, the High Court overturned the ban, ruling that the decision-making process by former Defra Secretary, Michael Gove, was unlawful. With such uncertainty over the future of metaldehyde, there is greater reliance on alternatives, such as Iron (Ferric) phosphate, biorationals, biologicals, physical barriers and agronomic/cultural practices. In addition, there are also concerns over biological invasions, especially relating to the Spanish slug, *Arion vulgaris*, which has established as a major agricultural pest across Europe.

The aim of this project was to collate global information on slugs and their various control options in order to enhance farming methods. The objectives of the study were to: characterise key slug species in the UK; identify potential slug invasions and their impact on biosecurity; determine direct and indirect economic risks of slugs; review slug monitoring systems; evaluate slug control options; determine the future of malacology; and to investigate novel commercial applications for slugs.

The countries visited included Australia, Belgium, Brazil, Canada, Japan, Kenya, New Zealand, United Kingdom, United States, South Africa and Spain. Researchers, farmers, government officials, entrepreneurs and businesses were interviewed, generating both qualitative and quantitative data.

Outputs of this study showed that the slug fauna of the UK is constantly evolving, with over 50% of slug species being exotic. Therefore, it is imperative that measures are put in place to prevent further slug invasions by developing robust biosecurity protocols. This is vital as slugs cause significant direct economic damage to crops and have an indirectly impact on human and animal health, rejection of contaminated exports and soil health.

With the future of metaldehyde uncertain, Iron (Ferric) phosphate may be the only ‘chemical’ control option available going forward. Demand could exceed supply, and with no information as to whether resistance could develop, the future of chemical slug control is unknown. It is likely that the uncertainty will lead to an increased uptake in bio-molluscicide products, but these must first be financially feasible for broadacre crops. Agronomic/cultural practices are also playing an increasing role, especially in minimum tillage and direct drilling systems.

Monitoring is important; however current methods are labour intensive so there is a drive to incorporate technology, especially real-time mobile systems.

Monitoring, as well as chemical, biorational, biological, physical barriers and agronomic/cultural control practices, should be incorporated into a slug integrated pest management (IPM) strategy pyramid, tailor-made to each field.

The future of malacology feels uncertain, with no clear succession plan in place and limited opportunities for researchers to share and develop ideas. We need to promote the subject to the next generation and encourage opportunities for knowledge sharing.

Finally, if slugs are so difficult to control, are we missing a trick? Should we be farming them instead?

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DISCLAIMER

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1. Introduction

I grew up on my family's mixed farm in Aberdeenshire, with the stunning Cairngorm National Park as my daily backdrop. Agriculture is well and truly in my blood, with both my mum and dad coming from farming families. However, just like many others, I was encouraged to get off the farm and study something different. Initially this was an honours degree in Forensic Science but after fighting crime in the big smoke (Aberdeen), the lure of agricultural life crept in. I decided to go back to university to study for a PhD in Environmental Science after being inspired by a very enthusiastic academic at the University of Aberdeen who was working on slug control. Slugs had always been something that fascinated me when growing up but I never imagined I could turn them into a career. However, maybe having a background in forensic science would make me the perfect slug detective?

Figure 1: Dr Jenna Ross, slug expert and author of this report (Source: Author)

My PhD was focused on improving the production efficiency of BASF's (formally Becker Underwood) biological molluscicide product for the agricultural and horticultural sectors. On completion of my PhD studies I was lucky enough to secure a Knowledge Transfer Partnership project with BASF, focused on enhancing biological slug control. During this time, I was given the opportunity to study towards a Chartered Management Institute Level 5 Diploma in Management and Leadership, which inspired me to assess the commercial value of my research. I went on to do a short-term contract in Norway focusing on the Spanish slug, *Arion vulgaris*, before securing a grant to work on developing new commercial bio-molluscicide solutions in South Africa.

In addition to my slug research, I spent a year's secondment at the International Institute of Tropical Agriculture in Tanzania, educating local farmers on the identification of plant pests and diseases and the appropriate use of chemical pesticides.

I have published a number of peer review journal articles and book chapters and have worked as a freelance scientific and agricultural journalist. I am also heavily involved in the scientific community, and in 2019, following the publicity of my Nuffield Farming scholarship, was invited to convene the International Organisation for Biological and Integrated Control (IOBC) Slug and Snail conference in Valencia, Spain.

I consider myself a champion of lifelong learning, acting as an Industry Champion for LANTRA, a STEM ambassador for local schools and a PhD supervisor at Stellenbosch University, South Africa.

In 2018, I graduated with an MBA, allowing me to test the feasibility of my slug control ideas. It is fair to say that I am truly passionate about my work and I am determined to find an effective and innovative way of controlling slug pests. My Nuffield Farming project has allowed me to review the current global slug control market thus allowing me to assess where my research and commercial interests fit into the bigger picture. This inspired me to accept a position with Crop Health and Protection (CHAP), one of the new AgriTech centres, to make my ideas a reality.

In summary, I hope this report helps UK farmers and avid gardeners assess their current control strategies and get to grips with these slimy creatures. I also hope my findings highlight the importance of having robust biosecurity protocols in place in order to prevent future biological invasions of slugs into the UK.

2. Background

Terrestrial gastropod molluscs (snails and slugs) are important economic pests worldwide, targeting an array of agricultural and horticultural crops (Barker, 2002).

The terms 'snail' and 'slug' relate to the two body shapes:

1. **Snails** (Fig. 2) have a coiled shell in which the body of the animal can retract. The shell is a hollow spiral tube made up of calcium carbonate. It is non-living, but grows as the animal matures (e.g. like a human fingernail)

Figure 2: Body shape of a snail (Source: Dr Suzete Gomes)

2. **Slugs** (Fig. 3) have evolved from snails, and have a shell that is significantly reduced or completely lost (South, 1992).

Figure 3: Body shape of a slug (Source: Author)

In the UK slugs are more of an economic pest than snails, so this report will primarily focus on slugs.

The main morphological features of a slug are detailed in Fig. 4.

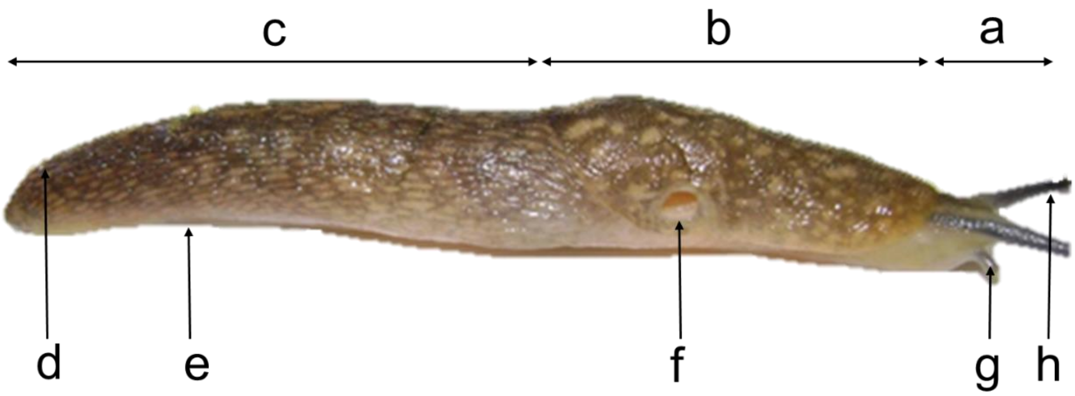


Figure 4: Basic slug morphological features: (a) head, (b) mantle, (c) tail, (d) keel, (e) foot sole, (f) pneumostome or breathing pore, (g) sensory tentacle, and (h) ocular tentacle (Source: Author)

Slugs have both sex organs so they can reproduce by means of either amphimixis (sexual reproduction) or hermaphroditism, and the hermaphrodites can either be self- or cross- fertilising. The life cycle varies between slug species, with some species being opportunistic breeders, producing multiple generations within one year, while others can be annual breeders, or in some instances, breed over several years. Slugs lay eggs in batches of 10 to 50 eggs, with up to 500 eggs being produced per slug over a series of weeks (Barker, 2001).

Slugs attack crops at various stages of development. They can reduce the vigour of plants by destroying seedlings, causing seed hollowing, damaging stems and growing points, and diminishing the leaf area (South, 1992) (see Fig. 5). Tolerance to slug damage varies from small cosmetic damage, through to entire loss of crop, resulting in huge economic losses for farmers (Willis *et al*., 2006).

Figure 5: Slug damage to Brussels sprouts (Source: Author)

Current methods for controlling slugs in the UK rely heavily on the application of chemical molluscicide pellets, containing either metaldehyde or Iron (Ferric) phosphate. However, in December 2018, the Department for Environment, Food and Rural Affairs (Defra) made the decision to ban the outdoor use of metaldehyde due to its impact on birds and mammals (Gov, 2018a). Conversely, in July 2019, the High Court overturned the ban, ruling that the decision-making process by former Defra Secretary, Michael Gove, was unlawful, leaving the future of chemical slug control up in the air (Jones, 2019).

In addition to the controversy over chemical molluscicides, there are also concerns over biological invasions, especially relating of the Spanish slug, *A. vulgaris*, which has established as a major agricultural pest across much of Europe (Kozlowski, 2007). However, little is known about the impact and extent of the distribution of this slug species in the UK, as well as other potential slug invasions.

Finally, with a huge amount of money invested in controlling slugs in the UK, perhaps there is an opportunity being missed to utilise these animals, and their bi-products, as a commercial venture.

3. Aim and Objectives

3.1 Aim

The aim of this project was to collate global information on slugs, and their various control options, in order to enhance farming methods in the UK.

3.2 Objectives

The objectives of the project were to:

1. Characterise the key slug species in the UK;
2. Identify potential slug invasions and their impact on biosecurity;
3. Determine direct and indirect economic risks of slugs;
4. Review slug monitoring systems;
5. Evaluate slug control options;
6. Determine the future of malacology; and
7. Investigate novel commercial opportunities for the utilisation of slugs

4. Research Approach and Methodology

The countries visited as part of this research project included Australia, Belgium, Brazil, Canada, Japan, Kenya, New Zealand, United Kingdom, United States, South Africa and Spain. A mixture of researchers, farmers, government officials, entrepreneurs and businesses were visited. Table 1 illustrates the itinerary and the objectives covered by the study tour.

Table 1: Study tour itinerary, contacts and objectives covered (Source: Author)

Date	Country	Contact	Objectives (refer to section 3.2)
February 2018	Brazil	Dr Suzete Gomes, Laboratório de Malacologia, Rio de Janeiro	2, 3, 6, 7
		Mr Rildo Belarmino, Sao Paulo	5, 6
		Dr Ana Rita de Toledo-Piza, Limace Biotechnologia, Sao Paulo	6, 7
	United Kingdom	Mr Mike Inglis, Mollusckit, Aberdeen	5
		Dr Andy Evans, SRUC, Edinburgh	3, 5, 6
May 2018	Kenya	Dr Solveig Haukeland, International Centre of Insect Physiology and Ecology, Nairobi	2, 3, 5, 6, 7
		Dudutech, Naivasha, Kenya	5
	United States	Dr Pamela Marrone, Marrone Bio Innovations, Davis	5
		Dr Rory Mc Donnell and Dr Dee Denver, Oregon State University, Corvallis	2, 3, 5, 6, 7
		Dr Irma De Lay, University of California-Riverside, Riverside	5, 6
		Dr David Robinson, USDA, Philadelphia	2, 3, 5, 6, 7
June 2018	Canada	Dr Lien Luong, University of Alberta, Edmonton	5
		Mr Rod Bradshaw, farmer, Edmonton	3, 5
		Ms Kristina Polziehn, Axiom Agronomy, Edmonton	3, 5
	United Kingdom	Dr Lothar Ott and Mr Eric Gussin, Lonza, Basel	3, 5, 6
July 2018	Japan	Ci:z.Labo, Tokyo	7
August 2018	New Zealand	Dr Michael Wilson, Consultant, Hamilton	1, 2, 3, 5, 6
		Mr Allister Holmes, Foundation for Arable Research, Feilding	3, 5
		Mr Malcolm White, farmer, Napier	3, 5
		Mr Duncan Thomas, H&T, Feilding	3, 5
		Mr Frank Collier, farmer, Feilding	3, 5
		Mr Douglas Giles, farmer, Feilding	3, 5
		Mr Mike Swift, Lonza, New Plymouth	5
		Dr Stuart Davis, Sutherland Produce, Bombay	3
	Australia	Mr Stewart Learmonth Department of Primary Industries and Regional Development (DPIRD), Manjimup	3, 4, 5, 6
		Ms Svetlana Micic Department of Primary Industries and Regional Development (DPIRD), Albany	3, 4, 5, 6

		Mr Andrew Slade, farmer, Albany	3, 5
		Dr Greg Baker & Dr Kym Perry, South Australian Research and Development Institute (SARDI), Adelaide	2, 3, 5, 6
		Dr Michael Nash, Consultant, Melbourne	2, 3, 4, 5, 6
		Dr Helen Billman-Jacobe, Melbourne	5
	Canada	Dr Lien Luong, University of Alberta, Edmonton	5
September 2018	Belgium	Dr Ziga Laznik, University of Ljubljana, met at the European Society of Nematologists, Ghent	2, 3, 5, 6
		Dr Geoffrey Jaffuel, University of Neuchâtel, met at the European Society of Nematologists, Ghent	5, 6
		Dr Robbie Rae, Liverpool John Moores University, met at the European Society of Nematologists, Ghent	5, 6
		Ms Nadine Sydow, Founder of Solvoluta, Brussels	5, 6
November 2018	South Africa	Mr Christiaan Jansen van Rensburg, Orchard, Worcester	3, 5
		Ms Annika Pieterse, Stellenbosch University, Stellenbosch	3, 5, 6
		Vergenoegd, Stellenbosch	5
December 2018	United Kingdom	Dr David Cameron, De Sangosse, Cambridge	3, 4, 5
		Dr Gordon Port, Newcastle University, Newcastle	1, 3, 4, 5, 6
		Dr Ben Rowson, National Museum Wales, Cardiff	1, 6, 7
		Dr Hayley Jones, Royal Horticultural Society	1, 3, 4, 5, 6
		Ms Emily Forbes, Harper Adam University, Edgmond	4, 6
January 2019	United Kingdom	Mr Graham Potter, farmer, met at Sustainable Landscapes Slug Masterclass	3, 5
		Mr Morley Benson, Certis, met at Sustainable Landscapes Slug Masterclass	5
July 2019	Spain	Mr Francois Benne, De Sangosse, met at International Organisation for Biological and Integrated Control Slug & Snail conference	4
		Dr Bjorn Hatteland, NIBIO, met at International Organisation for Biological and Integrated Control Slug & Snail conference	5

Each visit involved a structured interview, generating both qualitative and quantitative data. Notes were written up after each meeting and formulated into this report. Data has since been disseminated through various vehicles, including blogs (e.g. CABI blog), a monthly column in the Farmers Journal Scotland, AHDB newsletters, as well as various presentations at knowledge exchange events and conferences.

5. Slug Species in UK

5.1 Slug Species

Dr Ben Rowson (Fig. 6), from the National Museum Wales, Cardiff, suggests that the slug fauna of the UK is constantly evolving. He estimates that there are:

- 42 slug species currently described from the UK;
- Two additional slug species found in Ireland;
- Three species of semi-slug;
- One recently introduced species of semi-slug, recorded in 2014; and
- One newly introduced milacid species, which was recorded in 2018 and is currently undergoing identification.

Of these species, it is estimated that 18 are native, with the remaining species being introduced. This means that over 50% of slug species in the UK are exotic (Rowson *et al.*, 2014).

Figure 6: Dr Ben Rowson, from the National Museum Wales, Cardiff (Source: Author)

By far the most troublesome slug species is the grey field slug, *Deroceras reticulatum*, due to its widespread distribution, and attraction to major agricultural and horticultural crops (South, 1992). This species was present in all countries visited, and is easily identifiable, with its medium size (grows to approximately 50 mm), it's grey, cream or brown colour, and the fact it produces a milky white mucus when disturbed (Rowson *et al.*, 2014) (see Fig. 7).

Figure 7: Grey field slug, *Deroceras reticulatum* (Source: Author)

Figure 8: Selection of pestiferous slug species (a) *Deroceras invadens*; (b) *Milax gagates*; (c) *Arion vulgaris* (Source: Author)

Additional problematic slug species in the UK include other *Deroceras* spp., the *Arion* garden slugs (*Arion hortensis* and *A. distinctus*), the keeled slugs (*Boettgerilla*, *Milax* and *Tandonia* spp.) and the Spanish slug, *A. vulgaris* (Rowson *et al.*, 2014) (see Fig. 8).

There has been an explosive population growth of *A. vulgaris* in Central and Northern Europe over the last five decades, indicating extreme invasive nature. In Norway, *A. vulgaris* is now so widespread, that slugs are being collected from the Arctic circle (Fig. 9).

Figure 9: *Arion vulgaris* collected from the Arctic circle in Norway (Source: Author)

The term, *A. vulgaris*, is often used interchangeably with *A. lusitanicus* in the literature, however this is incorrect. The slug species *A. lusitanicus* is believed to be endemic to central Portugal, whereas the type locality of *A. vulgaris* is the Atlantic South West France (Chevallier, 1974; Proschwitz, 2009), or central Europe (Pfenninger *et al.*, 2014). In addition, these species differ both morphologically and molecularly (Castillejo, 1997, Quinteiro, 2005, Proschwitz, 2009, Hatteland *et al.*, 2011; 2015).

The mechanism for successful colonisation of *A. vulgaris* in Europe is poorly understood, but it is likely that the animal shows flexible behavior, and is released from its co-evolved natural enemies, thus allowing it to adapt to new environments (Ross *et al.*, 2010; 2016).

Dr Ben Rowson, National Museum Wales, points out that *A. vulgaris* is relatively widespread in the UK, with the NBN Atlas (2019) showing reports of this slug species from the northern tip of Scotland, right down to the southern tip of England (Fig. 10).

Figure 10: Distribution of *Arion vulgaris* in the UK (Source: NBN Atlas, 2019)

However, despite the widespread distribution of *A. vulgaris* in the UK, little is known about its pest status. Dr Rowson confirms he has received samples of *A. vulgaris* collected from damaged agricultural crops, but suggests that the only method to fully understand the status and distribution of this species is to conduct systematic sampling across the country.

5.2 Slug Identification

Identifying the slug fauna in the UK can be done using various guides, such as Rowson *et al.* (2014) (see page 91). However, Dr Rowson points out that several species, especially members of the Arionidae family, need to be dissected in order to confirm to species level. *Arion vulgaris* can look identical to *A. rufus* with the naked eye but, on dissection, they differ in their reproductive system (Fig. 11).

Figure 11: Dissections differentiating between *Arion rufus* (left) and *A. vulgaris* (right), collected from a farm near Loughborough (Source: Dr Ben Rowson)

Dr Gordon Port, from Newcastle University, and Dr Hayley Jones, from the Royal Horticultural Society, are involved with a new PhD project that aims to make the identification process easier by using a phone application, whereby slugs can be identified to family level. This could be hugely beneficial to both farmers and gardeners.

5.3 Chapter Questions

- Can a systematic survey of *A. vulgaris* be conducted to determine its distribution and economic impact on agricultural crops in the UK?
- Can slug identification be enhanced using novel technologies?
- What other slug species may be potential invaders to the UK and how do we monitor this?

6. Potential Slug Invasions and Biosecurity Threats

6.1 Biological Invasions

Slugs and snails are excellent invaders due to their high reproductive rates and their environmental tolerance, and they thrive in association with humans (synanthropic) (Grimm *et al*., 2009). In addition, when entering new habitats, they are freed from their natural predators and parasites, and flourish in their new unoccupied ecological niches (Ross *et al*., 2010).

6.2 Potential Slug Invasions

Dr David Robinson (Fig. 12), of United States Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS), is a key member of the Plant Protection and Quarantine (PPQ) team, whose objective includes preventing the introduction of invasive mollusc species into the United States, and its territories, in order to protect the agricultural industry and the natural resources of the US.

Figure 12: Dr David Robinson, United States Department of Agriculture (USDA) (Source: Author)

Dr Robinson identifies three key species that are seen as potential invasive threats to the US:

- *Arion vulgaris* ("Spanish slug");
- *Veronicella cubensis* ("Cuban Slug"); and
- *Parmarion martensi* ("Semi-slug").

Dr Robinson confirms that the UK has already been invaded by *A. vulgaris* and must stay vigilant in order to prevent the introduction of the other two species listed above.

6.2.1 *Veronicella cubensis*

The USDA is worried about *V. cubensis* (Fig. 13) entering US soil after its devastating impact on the Mariana Islands. It was first introduced there in the 1990's, first to the island of Guam, and then to the island of Rota in 1997. The species is now widespread throughout Rota, with population levels exceeding anywhere else in the world. This has had a devastating impact on crops in Rota (Fig. 14), where the economy is heavily dependent on agriculture (Robinson and Hollingsworth, 2004).

Figure 13: *Veronicella cubensis* ("Cuban Slug") (Source: Dr David Robinson)

Figure 14: Damage caused by *Veronicella cubensis* in Rota (Source: Dr David Robinson)

6.2.2 *Parmarion martensi*

The USDA is concerned over the invasive semi-slug, *Parmarion martensi* (Fig. 15), after it has had a major impact on human health in the Hawaiian Islands by transmitting the rat lungworm, *Angiostrongylus cantonensis* (Hollingsworth *et al*., 2007). Rats are hosts to the parasite, and the larvae of the parasite are then passed through the faeces of the rat, which are then subsequently eaten by the slug. Humans then contract the parasite by eating contaminated raw fruit and vegetables. The infection can cause a rare type of non-recoverable meningitis (Hollingsworth *et al.*, 2007). A recent report by Johnston *et al*. (2019) demonstrated that 82 people have contracted the rat lungworm from 2007 to 2017 in Hawaii, causing a range of symptoms, including headaches, arthralgias, vomiting, myalgias and a stiff neck. Of the 82 cases, 65 were hospitalized and two died.

Figure 15: *Parmarion martensi* (Source: Photo taken by the late Dr Rob Hollingsworth)

6.2.3 *Meghimatium pictum*

Dr Suzete Gomes, from the Laboratório de Malacologia, Rio de Janeiro, identifies *Meghimatium pictum* (Fig. 16) as another slug species to be concerned about. It is native to China, but has invaded the States of São Paulo, Paraná, Santa Catarina and Rio Grande do Sul in Brazil (Gomes *et al.*, 2011). It is likely that the slug was accidentally introduced to Brazil through importation of agricultural products. The USDA has reported that *Meghimatium* spp. have been intercepted by US port officials from shipments of *Bougainvillea* sp., bonsai, orchids and mushrooms being imported from China and Taiwan. This slug species also harbours the human parasite, *Angiostrongylus costaricensis* (Rodriguez *et al.*, 2018).

Figure 16: *Meghimatium pictum* in Brazil (Source: Dr Suzete Gomes)

See Appendix 1 for a list of other potential slug threats (page 78).

6.3 Protecting Biosecurity

Slugs and snails pose a significant biosecurity risk because they:

- Have a varied diet, and can be herbivores, predators, scavengers or omnivores;
- Have the ability to carry parasites and pathogens, including human diseases;
- Can adapt to disturbed environments thus flourish in association with human activity;
- Can reproduce rapidly and lay hundreds of eggs over a series of weeks;
- Are self-fertilising, so can survive without a mate, and can establish a new population with a single invader; and
- Can aestivate, meaning they can become dormant, and emerge when weather conditions are favourable (Department of Agriculture and Water Resources, 2017).

The UK is particularly vulnerable to slug and snail invasions, due to its mild damp climate, thus making it the ideal breeding ground.

6.4 Biosecurity Planning

Biosecurity planning provides a mechanism for practices and procedures to be put in place that will rapidly detect an incursion, thus minimising the risk of the pests becoming established.

Dr David Robinson, from the USDA, plays a key role in helping to eradicate or control molluscs in the US. He trains port identifiers in malacology (study of molluscs) across 27 inspection stations (e.g. ports, airports etc.). The US has strict laws on the movement of molluscs, even between states, and they are particularly protective over Florida and California, due to the production of high value crops.

6.5 Principal Pathways

Table 2: Principal pathways for introduction of molluscs into the US (Source: Dr David Robinson, USDA)

Principal Pathway	Case Study
Cut flowers, plant material and fresh vegetables	The Spanish slug, *A. vulgaris*, has been intercepted in rhubarb imported from Europe.
Tiles and quarry products	Italy is a major producer of tiles, and previously molluscs have been found adhering to the underside of the tiles. This has been addressed by introducing a pre-inspection phase in Italy prior to shipment.
Exterior of containers	95% of molluscs intercepted are from the exterior of containers. Snails can survive for up to 12 months on the outside of containers.
Intentional introductions	Hawaii is known for having a number of mollusc species that are not present on mainland US. Passenger baggage is inspected daily in Hawaii, to prevent passengers from carrying the Giant African Snail back to the US as pets. Other common intentional pathways include the use of molluscs as a food source, for scientific research and for religious purposes.

6.6 Biosecurity Protocol in the US

The US biosecurity protocol for mollusc interceptions involves:

- Preliminary identification and photography of the specimen;
- Dissection and photography of the reproduction system;
- National specialist then makes a recommendation; and
- Port makes the final decision to either:
  - Treat: This includes metaldehyde, cold treatment, methyl bromide etc.
  - Not to treat: This includes re-exporting container, returning to port of origin, or incineration of perishable goods.

To date, the USDA can identify molluscs within 15 minutes.

A proposed biosecurity protocol for the UK is detailed in Appendix 2 (page 79).

6.7 Successful Eradications

The US provides a fantastic success story, whereby they have eradicated the invasive Giant African Snail, *Lissachatina fulica* (Fig. 17), from Florida, using out-of-the-box thinking.

Figure 17: *Lissachatina fulica*, Giant African Snail (Source: Dr Suzete Gomes)

The USDA has employed a citizen scientist scheme that includes local schools, as well as deploying specially trained sniffer dogs, to identify the specific species (see Appendix 3 for more details, page 80). Perhaps this could be applied to eradicating *A. vulgaris* in the UK? (See Appendix 4, page 81).

6.8 Chapter Questions:

- What biosecurity protocols need to be put in place to prevent future invasions of key slug species into the UK?
- What are the key principal pathways for molluscs invading the UK?
- Can the Spanish slug be successfully eradicated from the UK using novel strategies, such as citizen scientist programmes and sniffer dogs?

7. Economic Risks of Slugs

The economic risks associated with slugs can be broken down into:

- **Direct Risks:** Impact of slugs themselves, such as feeding damage, faecal and mucus contamination of crops, and clogging of harvesting machinery; and
- **Indirect Risks:** Impact associated with downstream consequences, such as the transmission of parasites and diseases, and contamination of exported produce, resulting in the down-grading or rejection of shipments by quarantine inspectors. In addition, the impact of tillage and burning to control slugs has an indirect impact soil health (Hertbert, 2010).

7.1 Direct Economic Risk

Slugs are generalist feeders, causing significant economic damage to a broad range of crops, including arable crops, horticultural crops and ornamentals (Barker, 2002).

In the UK, one of the most vulnerable crops is oilseed rape because the growing point of the germinating shoot is above ground, and remains at risk until the four true leaf stage. Modern day varieties of oilseed rape have a higher susceptibility to slug damage due to the lower levels of glucosinolates (Glen and Moens, 2002; Moens and Glen, 2002; AHDB, 2018). Oilseed rape, and its counterpart canola, was by far the most susceptible crop on my travels, with damage recorded in South Africa (Fig. 18), US, Canada, Australia, New Zealand and across Europe.

Figure 18: Slug damage in South African canola crop (Source: Mr Geoff Tribe)

Another crop that is significantly affected by slugs is winter wheat (Fig. 19), which is susceptible after the seeds are sown and begin to absorb water. The slugs kill the seeds by feeding on the embryo and endosperm, causing the characteristic 'seed hollowing', with each slug having the ability to kill 50 seeds within the first week of sowing. Slugs cause shoot and leaf damage up until growth stage (GS) 14; however winter wheat remains vulnerable until GS21 (Glen and Moens, 2002; AHDB, 2018).

Figure 19: Wheat damage near Melbourne, Australia (Source: Author)

Dr Michael Nash, a consultant based near Melbourne, points out that oats and barley have an advantage over wheat, in that their seeds have an extra coat making them less vulnerable, however once the seeds germinate, shoots and roots are susceptible.

Slugs are a major pest of corn in North America (Hammond and Byers, 2002). Mr Blake Vince, from Ontario, Canada, says that slugs cause major defoliation in his corn crops (Fig. 20).

Figure 20: Slug damage in corn in Canada (Source: Mr Blake Vince)

The Agricultural and Horticultural Development Board (AHDB) reports major damage to potato production (AHDB, 2018). Slugs enter the tubers creating small holes in the skin, and then hollow out cavities in the tissue underneath.

Field vegetables are highly susceptible to slug damage from sowing through to harvest. Slugs can damage a range of vegetables including lettuce, Brussels sprouts, broccoli, cabbage, cauliflower, carrots and asparagus (Port and Ester, 2002). Vegetable damage was recorded in all countries visited.

In some crops a small amount of slug damage can be tolerated, however in crops such as lettuce and Brussels sprouts, retailers have a zero-tolerance policy to slug damage. In other crops, such as asparagus, slug damage may result in the crop being downgraded or rejected.

As part of this study, it was discovered that slugs were a major pest of kale in Kenya (Fig. 21).

Figure 21: Slug damage in Kale in Kenya (Source: Dr Solveig Haukeland)

Dr Michael Wilson, who is a slug expert based in Hamilton, New Zealand, confirms that slugs are also a pest of pasture in New Zealand. Clover is particularly susceptible, especially during establishment, with slug damage resulting in reduced nitrogen fixation. Slugs target seeds, damage young shoots, and reduce vigour of plants by removing cotyledons and young leaves (Wilson and Barker, 2011).

Mr Stewart Learmonth, from the Department of Primary Industries and Regional Development's Agriculture and Food division in Western Australia, demonstrated that slugs are a major pest of truffle (Fig. 22). Slugs produce deep and uneven cavities in the truffle, leading to the downgrading which can have a significant impact on profitability.

Figure 22: Slug damage to truffle in Manjimup, WA, Australia (Source: Author)

Mr Rildo Belarmino, from Brazil, confirmed that their biggest problem is slug damage in corn and soybean (Fig. 23). Slugs feed on the leaf tissue throughout the growing season, reducing growth. However, often the damage is only cosmetic, and the crop can outgrow slug damage. Damage in corn and soybean was also recorded in the US, Canada, Australia and New Zealand.

Figure 23: Slug damage in Beans in Brazil (Source: Mr Rildo Belarmino)

In Brazil, Dr Suzette Gomes has conducted research on slug damage in vineyards, with losses recorded in Niagara and Bordô grapevines during the harvesting season. Slugs feed on the pulp of the fruit.

In France, Mr Eric Gussin, from Lonza Group, confirms that slugs are a major pest of sunflowers.

7.2 Indirect Economic Risk

7.2.1 Health Risk

Molluscs act as intermediate hosts for a number of parasites, and pose a health risk to humans and livestock, as well as other animals (Grewel *et al*., 2003).

7.2.1.1 Risk to Human Health

Dr Suzete Gomes, from the Laboratório de Malacologia in Rio de Janeiro, Brazil, states that there are four main human diseases than can be contracted from parasites that use molluscs as intermediate hosts:

- **Eosinophilic meningitis** is caused by the nematode, *Angiostrongylus cantonensis*, which is also known as the rat lungworm (CDC, 2019a). Any species of mollusc can act as the intermediate host, however, the Giant African Snail, *Lissachatina fulica*, is considered the main host and offers the highest risk of transmission, due to its abundance in urban areas.

- **Abdominal angiostrongyliasis** is caused by the nematode, *Angiostrongylus costaricensis*, and again, any terrestrial species of mollusc can act as the intermediate host (CDC, 2019a). However, species within the Veronicellidae slug family are considered the main intermediate hosts. Dr Gomez adds that this year they discovered that the invasive slug species, *M. pictum* (Fig. 16) was infected by *A. costaricensis* in Brazil (Rodriguez *et al.*, 2018).
- **Schistosomiasis** is caused by the trematodes *Schistosoma haematobium*, *S. japonicum*, *S. mansoni*, *S. mekongi* and *S. intercalatum* and is transmitted by various freshwater mollusc species. This is particularly problematic in parts of Africa (CDC, 2019b).
- **Fascioliasis** is caused by the trematode, *Fasciola hepatica*, which is also known as 'the common liver fluke' or 'the sheep liver fluke', as well as *F. gigantica*. Again, like schistosomiasis, these species are transmitted by various freshwater mollusc species (CDC, 2019c).

7.2.1.2 Risk to Animal Health

Molluscs can act as intermediate hosts for a number of animal parasites, and can have a significant impact on farm profitability regarding livestock health (COWS, 2019a). These parasites include:

- The trematode *Fasciola hepatica, also known as the 'liver fluke',* which is carried by the mud snail *Galba (Lymnaea) truncatula*, and causes fascioliasis in cattle and sheep, as well as rabbits, deer and horses (COWS, 2019a; SCOPS, 2019a); and
- Various nematodes, or lungworm, including *Dictyocaulus filaria, Muellerius capillaris*, *Protostrongylus rufescens*, *Dictyocaulus viviparus* and *Cystocaulus* ocreatus. COWS (2019b), Grewel *et al.* (2003) and SCOPS (2019b) provide detailed lists of the main nematode species.

Information relating to treatment of these parasites can be found at COWS (2019cd) and SCOPS (2019cd).

7.2.2 Rejection of Exported Crops

Exported crops can be rejected due to the presence of faecal and mucus contamination, or the presence of live or dead slugs and snails, or eggs. Dr Greg Baker and Dr Kim Perry from SARDI, Adelaide, Australia, are working on how to reduce the problem of snail contamination in harvested wheat crops for export. The aim is to achieve a tolerance level of 1 snail in 2.25 litres of grain. The four main snail species that are causing these contamination issues include *Theba pisana*, *Cochlicella Barbara*, *C. acuta* and *Cernuella virgate*.

7.2.3 Soil Health

Cultivation is heavily relied upon as a cultural method to control slug numbers around the world; however, this can have an indirect impact on soil health by increasing soil erosion and lowering levels of organic matter in the soil. In Australia, burning is still part of the advised protocol under the 'Bash'Em, Burn'Em, Bait'Em' guidelines (SARDI, 2003), which can also have an impact on soil health.

7.3 Chapter Questions

- How can we put a monetary value on the direct and indirect economic impact of molluscs?
- Do the snail species *T. pisana*, *C. Barbara*, *C. acuta* and *C. virgate* pose a threat to UK agriculture?
- How can mollusc contamination of harvested crops be avoided?
- What systems need to be put in place to monitor the impact of slugs on human and animal health? And how does this relate to one health?
- What slug control practices can be employed that don't impact soil health?

8. Slug Monitoring Systems

8.1 Novel Monitoring Systems

Dr David Cameron, from De Sangosse, and Chairman of the Metaldehyde Stewardship Group (MSG), states that monitoring slugs plays a key role in reducing unnecessary applications of chemical molluscicides, and ensures maximum protection to the environment, with particular focus on water, birds and small mammals. It is an important tool in protecting crops and boosting productivity.

However, many farmers interviewed during this study stated that they do not have time for traditional monitoring systems (Appendix 5, page 82), and want a more robust method for monitoring slugs that is less labour intensive.

One such solution is Limacapt, a new monitoring system developed by Cap2020 and De Sangosse. Mr Francois Benne, from De Sangosse, says that Limacapt is a self-powered sensor that can automatically count slugs based on an algorithm that processes infrared images.

Modelling technology may also provide a useful tool for monitoring slug populations. Ms Emily Forbes, who is a PhD student at Harper Adams University, has been investigating how modelling soil characteristics, such as organic matter, pH, moisture, temperature, and soil texture, could be used to determine where slugs are most abundant in a field, allowing for precision molluscicide application. In addition, Ms Forbes has also been experimenting using Radio Frequency Identification (RFID) technology (e.g. like the technology used to chip cats and dogs), to monitor slug movement patterns in cereal and oilseed crops (Fig. 24).

Figure 24: Ms Emily Forbes using Radio Frequency Identification to monitor slug movements in UK crops (Source: Ms Emily Forbes)

Ms Svetlana Micic and Mr Stewart Learmonth from the DPIRD in Western Australia, along with consultant, Dr Michael Nash, from Melbourne, and Dr Greg Baker and Dr Kim Perry from SARDI, Adelaide are looking to enhance monitoring systems in Australia. The project they are involved in uses time lapse cameras and environmental data to predict movement and feeding of slugs (Fig. 25). The environmental factors studied include soil temperatures, ambient temperatures, soil moisture, humidity and leaf wetness. The aim is to assist farmers with the timing of their bait applications.

Figure 25: Ms Svetlana Micic, from DPIRD in Albany, monitoring slug movement using time lapse cameras and various environmental factors (Source: Author)

The study is also focused on monitoring the biology and reproduction of slugs, in order to understand the life stages of slugs, and when best to apply baits (see Fig. 26).

Figure 26: Australian researchers are measuring the albumen gland, part of the reproductive system, to determine life stages of the slugs to enhance timing of bait application (Source: Author)

In addition, a rover (Fig. 27) has been deployed by DPIRD in Western Australia to gather photographic data on slug movements, to allow paddocks to be modelled. The aim, like Emily Forbes's study at Harper Adams University, is to employ precision molluscicide application.

Figure 27: Rover used by DPIRD to gather photographic data on slug movements in Albany (Source: Author)

8.2 Threshold Levels

Following slug monitoring, it is advised to refer to threshold limits before proceeding with bait applications (AHDB, 2018). These are detailed in Appendix 5, page 82.

8.3 Chapter Questions

- Can a real-time monitoring system for slugs be developed?
- Could this real-time monitoring system be mobile?
- Can monitoring systems be combined with control options to minimise costs?
- Are threshold limits accurate?
- How can threshold limits be improved?

9. Chemical Control

Chemical control of slugs has never been so limited. Firstly, methiocarb was removed from the European market in 2014/2015, and then in 2018, neonicotinoid seed treatments were banned (Jones, 2014; Gov, 2018b). In December 2018, Defra made the decision to ban metaldehyde, however, in July 2019, this decision was overturned. So, what does the future hold for chemical slug control?

9.1 Metaldehyde

To date (August 2019), it is still legal to buy metaldehyde products for outdoor use; however the future of this chemical slug control options is extremely uncertain.

9.1.1 What is metaldehyde?

Metaldehyde is an organic compound with the chemical formula $C_8H_{16}O_4$ (Pubchem, 2019a) (Fig. 28).

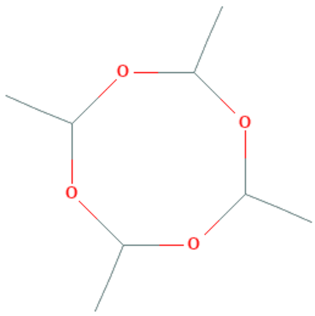


Figure 28: Chemical structure of metaldehyde (Source: Pubchem, 2019a)

9.1.2 How does metaldehyde work?

Metaldehyde is applied as pellets and is normally formulated with wheat bait. Metaldehyde acts on the mucus producing cells in slugs and snails, either through contact or ingestion, causing metaldehyde to be hydrolysed into acetaldehyde. This causes excess mucus secretion, convulsions and paralysis, with death usually following 1 to 2 days after exposure (Booze and Oehme, 1986).

9.1.3 Why is there a push to ban metaldehyde?

In December 2018, Defra announced a ban on metaldehyde, quoting the impact on birds and mammals as the key driver for their decision (Gov, 2018a). Conversely, in July 2019, this decision was overturned by the High Court, ruling that the decision-making process by former Defra Secretary, Michael Gove, was unlawful (Jones, 2019). However, metaldehyde has been under scrutiny for some time in the UK, due to its impact on water systems as it is frequently detected in surface water above the EU statutory drinking water limit of 0.1 µg L^{-1} (Castle *et al.*, 2017). This led to the establishment of the Metaldehyde Stewardship Group (MSG) in 2008, to encourage best practice regarding the use of metaldehyde pellets, and minimise the impact on the water systems and the environment. In 2017, MSG introduced additional measures to help protect birds and small mammals. See reference list for link to the Metaldehyde Stewardship Group (2019) guidelines (page 89).

Following the initial announcement to ban metaldehyde, Dr David Cameron, from De Sangosse and chairman of the MSG, said that the decision to ban metaldehyde was disappointing for the UK industry, and could bring competitive advantage to neighbouring European countries, as metaldehyde has been re-authorised for use in over 20 EU member states.

Dr Cameron also detailed the extensive work carried out by the MSG, and various water initiatives, including Severn Trent Water, who worked with 2000 farmers across 36,000 ha, rewarding farmers for reducing metaldehyde levels. Their efforts were shortlisted for the Environmental Award in the 2018 Utility Week Awards (Severn Trent Water, 2018).

9.1.4 What is the future of metaldehyde?

Despite the overruling of the ban of metaldehyde, the future of chemical slug control in the UK is extremely uncertain. However, beyond the UK market, metaldehyde is a popular chemical molluscicide used across the globe although a number of organisations appreciate the impact it has on the environment, and are therefore looking at innovative approaches to applying the chemical.

9.1.4.1 Baitchain/Wraptor

In South Africa, Mr Christiaan Jansen van Rensburg, Managing Director of Orchard Agrikem, has developed a new way of deploying metaldehyde pellets in fruit orchards. Rather than applying the pellets to the orchard floor, he has developed the Baitchain/Wraptor product. This involves a series of metaldehyde pellets moulded into a bead like structure, that is then thread through string material, and tied to the trunk of the tree. This then acts as a chemical and physical barrier all in one system (see Fig. 29), without having the negative environmental impact of having the chemical on the orchard floor.

Figure 29: Baitchain/Wraptor in use in the Western Cape, South Africa (Source: Ms Annika Pieterse)

9.1.4.2 Rappel™

In New Zealand, Mr Duncan Thomas, Business Manager for H&T, has been involved with developing metaldehyde seed treatments called Rappel™ (Fig. 30), which builds on initial studies conducted by Ester *et al.* (1996).

Figure 30: Rappel™ metaldehyde treated seeds (Source: Author)

Rappel™ contains five key components:

- Seeds: Quality and disease-free;
- Polymer: Ensures components adhere to the seed;
- Biostimulant: Humic/formic acid mixture to provide better drought defence;
- Saponins: Plant extract with bio-molluscicidal properties; and
- Metaldehyde: Chemical molluscicide.

In 2018, H&T had sold 12,500 ha of Rappel™ metaldehyde treated seeds in New Zealand. The price of Rappel™ is N$ 55/Ha, making it comparable to the cost of slug pellets, however, delivering less active ingredient to the environment.

Dr Michael Wilson, an independent mollusc expert based in Hamilton, New Zealand, suggests that molluscicidal seed treatments could play a key role moving forward (Fig. 31).

Figure 31: Dr Michael Wilson (right), independent mollusc expert, and, Allister Holmes (left), Foundation for Arable Research (Source: Author)

Dr Wilson proposes that seed treatments will get the crop up and past the highly vulnerable stage.

Mr Duncan Thomas, from H&T, also suggests that slugs avoid treated seeds and target weeds instead, possibly providing a double level of protection.

Rappel™ is currently being sold in New Zealand, and H&T are in the process of registering the product in other international markets. Their aim is to bring the product to the UK market through a joint venture distribution agreement with United Oilseeds, however this is dependent on the future of metaldehyde.

Mr Frank Collier, a farmer in the Feilding area (New Zealand), noted that his Rappel™ treated winter wheat had not had the same level of slug damage in 2018. This sentiment was echoed by Mr Douglas Giles (Fig. 32), a farmer and direct drill contractor, who had also witnessed less damage with the Rappel™ treated seeds.

Figure 32: Mr Douglas Giles, farmer and contractor in Feilding, New Zealand (Source: Author)

However, it should be noted that drilling the entire field with metaldehyde treated seeds would mean that the entire field will be treated with the active ingredient, making MSG guidelines difficult to adhere to. Treated seeds may also be unnecessary in areas of the field that have lower slug densities.

9.1.4.3 AXCELA™

In Europe, Swiss company, Lonza Group, has developed AXCELA™ (Fig. 33), which is a metaldehyde pellet, produced using a patent-pending wet-extrusion process. Gelatinisation alters the protein and starch structure of the flour, allowing water to be absorbed faster and therefore increasing palatability. Precision production means that the pellets are dust free and uniform in shape, resulting in unbiased distribution. Dr Lothar Ott, from Lonza Group, says that by maximising rainfastness and reducing the leaching of metaldehyde into the environment, AXCELA™ shows excellent environmental performance. Dr Ott also points out that the incorporation of Bitrex® (bitter substance) into the formulation, reduces the possibility of accidental consumption by humans, field wildlife and other mammals.

Figure 33: AXCELA™ product (Source: Author)

9.1.4.4 Improve feeding uptake of metaldehyde pellets

Ms Samantha de Silva, a PhD student from Newcastle University, has been working on the physiology and feeding preferences of slugs, particularly the grey field slug, *D. reticulatum*, in order to improve feeding uptake of metaldehyde pellets, and thus mortality. When slugs feed on food material, the rasping produces measurable acoustic data, and Ms. de Silva has used this information as a proxy for the amount of food material consumed. Analysis of this data can be used to determine the length of the feeding on slug pellets, the time it takes for the slug to find the pellet, the length of each bite, the total number of bites, the average bite length, and the average max bite amplitude.

Ms Amy Campbell, another PhD student at Newcastle University, has focused her studies on slug behaviour around metaldehyde pellets of different concentrations and formulations, in order to gather data to improve pellet design, increasing their acceptability and palatability to slugs.

9.2 Iron (Ferric) phosphate

Iron (Ferric) phosphate is the only chemical alternative to metaldehyde, and is certified for organic use.

9.2.1 What is Iron (Ferric) phosphate?

Iron (Ferric) phosphate is an inorganic compound with the chemical formula $FePO_4$ (Source: Pubmed, 2019b) (Fig. 34).

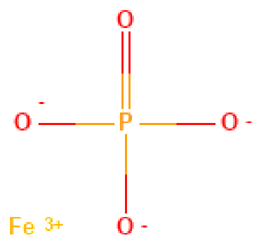


Figure 34: Chemical structure of Iron (Ferric) phosphate (Source: Pubmed, 2019b)

9.2.2 How does Iron (Ferric) phosphate work?

Iron (Ferric) phosphate is applied as a pellet, formulated with a bait to attract the mollusc. On ingestion, the Iron (Ferric) phosphate interferes with calcium metabolism in the gut of the target, causing the mollusc to stop eating, with death following three to six days later (Buhl *et al.*, 2013).

9.2.3 What is the future of Iron (Ferric) phosphate?

Iron (Ferric) phosphate is still a relatively new molluscicide compared to metaldehyde, with the latter being available since the early 1900's. This opens up lots of opportunities for research and development.

9.2.3.1 Sluxx HP

Mr Morley Benson, from Certis UK, explains that their Iron (Ferric) phosphate product, Sluxx HP®, is a superior product compared to dry and hybrid pellets, because it is produced using a wet processed pasta technique (see Table 3 for comparison of pellet types).

Table 3: Comparison of pellet production processes (Source: Morley Benson)

Dry Pellets	Hybrid Pellets	Wet Processed Pellets
• Ground wheat flour and bran • Produced using steam • Irregular size • Dusty • Cheap • Reduced quality • Limited spreadability	• Higher proportion of wheat – often Durum wheat • Produced under compression • More uniform • Less dusty than dry pellets • Increased quality • Increased persistence • Improved spreadability	• Contains Durum wheat • Produced from dough pushed through an extruder • Uniform shape • No dust • Superior quality • Superior persistence • Superior spreadability
Cost →		

The key components of a good molluscicide pellet include:

- Palatable
- Uniform
- Pellet size
- Crush strength
- Density
- Spreadability
- Rainfastness
- Anti-moulding

The application cost of Sluxx HP® compared to other products is detailed in Table 4.

Table 4: Cost of Sluxx HP® compared to other chemical molluscicide products (Source: Morley Benson)

Product	£/kg	% a.i.	Rate/ha	£/ha	Rate/ha	£/ha
Dry Pellets	1.12	3	4	4.48	7	7.84
Attract/Desire 1.5% wet	3.14	1.5	4	12.56	5	15.70
Trounce 1.5% Hybrid	1.55	1.5	4	6.20	7.5	11.63
Gusto Type	2.20	3	5	11.00	11.5	25.30
TDS Major	3.56	4	5	17.80	7	24.92
Derrex	2.40	3	4	9.60	5	12.00
Sluxx HP	3.10	3	4	12.40	5	15.50

Mr Benson concludes that the cost of applying a single application of a high-quality Iron (Ferric) phosphate pellet, such as Sluxx HP®, is comparable to applying multiple applications of dry pellets. He also states that the cost of applying a high quality wet processed Iron (Ferric) phosphate pellet is relative to applying a high quality wet processed metaldehyde pellet, but offers less environmental risk, and requires no buffer zone.

One key factor that was highlighted by Mr Benson, along with other agrochemical companies, is the importance for pellet applicators (Fig. 35) to be specifically calibrated for Iron (Ferric) phosphate. Also, baiting points and pellet dose rate should be relevant to the slug pressure in each field.

Figure 35: Slug pelleter (Source: Mr Graham Potter)

It should be noted that there is a debate as to whether Iron (Ferric) phosphate should be classified as a chemical or a biorational (discussed in Chapter 10). In addition, there are also concerns over Iron (Ferric) phosphate, after Langan and Shaw (2006) noted an increased mortality, decreased mass and reduced surface foraging in earthworms exposed to the substance.

9.2.4 Market Risks Associated with Iron (Ferric) phosphate

To date, Iron (Ferric) phosphate is still relatively new, and with uncertainty over the future of metaldehyde, little is known about the environmental impact we face if all farmers switch to an Iron (Ferric) phosphate programme.

One of the big questions with Iron (Ferric) phosphate is whether there will be sufficient supply to meet demand if metaldehyde is banned. Dr David Cameron, from De Sangosse and Chairman of MSG, points out that there are 13 plants in Europe manufacturing metaldehyde pellets, but very few producing Iron (Ferric) phosphate pellets.

However, the most concerning fact is that no studies have been conducted on the possibility of slugs and snails developing resistance to Iron (Ferric) phosphate. If metaldehyde is banned, this will be the only chemical molluscicide on the UK market, so usage will increase exponentially, and development of resistance could have a detrimental impact if it develops.

9.3 Chapter Questions

- Should metaldehyde be banned in the UK?
- If not, what opportunities would metaldehyde seed treatments offer?
- Is there enough supply of Iron (Ferric) phosphate to meet UK market demand if metaldehyde is banned?
- What is the possibility of slugs developing resistance to Iron (Ferric) phosphate?
- What other opportunities are there for the development of new chemical molluscicides?

10. Biorational Control

Biorationals are usually biologically derived; or if synthetic, are functionally and structurally similar to biologically occurring material (e.g. plant extracts, repellents, microbials etc.) (Matyjaszczyk, 2018).

10.1 Plants/Extracts

A number of plants and their extracts have shown to have molluscicidal, anti-feedant or attractant properties (Pieterse *et al.*, 2017a), including coffee, azadirachtin, cinnanamide, coriander, garlic, lichens, carvone, hemlock, yucca, opoponax, parsley, lichens and saponins, the latter of which has now been included as part of H&T's seed treatments (see section 9.1.4.2). Dr Rory Mc Donnell, from Oregon State University, has also conducted research in this area, and found that Clove bud oil (LC50: 0.027%) was most toxic to the snail *Cornu aspersum*, followed by pine (LC50: 0.082%) and spearmint (LC50: 0.103%) (Mc Donnell *et al.*, 2016).

10.2 Recycled Gypsum

Yorkshire farmer, Mr Graham Potter, has found that recycled gypsum can be used to control slugs through desiccation (Fig. 36).

Figure 36: Recycled Gypsum to control slugs (Source: Mr Graham Potter)

10.3 Chapter Questions

- Are biorational products financially feasible?
- What level of specificity do biorational products offer?
- What are the opportunities for microbials (bacteria, fungi and viruses) to control molluscs?

11. Biological Control

Biological control is the use of living natural enemies to control other living organisms (FAO, 2019).

11.1 Predators of Slugs

Molluscs have a number of predators, including birds, rats, frogs, lizards, centipedes, beetles and millipedes (Barker and Efford, 2004).

In South Africa, Vergenoegd Wine Estate uses Indian runner ducks (Fig. 37) to control molluscs in their vineyards. This has now developed into a tourist attraction, with 3000 tourists coming to watch the duck parade each month.

Figure 37: Vergenoegd uses ducks to control molluscs in their vineyards in Stellenbosch, South Africa (Source: Author)

Carabid beetles (Fig. 38) have also shown promise for controlling slug populations. Dr Bjorn Hatteland, a researcher from Norway, has shown that the carabids *Pterostichus niger*, *P. melanarius*, *Carabus nemoralis* and the staphylinid *Staphylinus erythropterus* all have the ability to feed on slug eggs and newly hatched slugs. *Carabus nemoralis* also has the ability to consume juvenile slugs up to one-gram fresh weight, and shows no preference for specific slug species, but will target the most abundant prey (Hatteland *et al.*, 2010; 2013).

Figure 38: The carabid beetle, *Carabus nemoralis*, feeding on a slug (Source: Dr Bjorn Hatteland)

11.2 Parasites of Slugs

Molluscs can be infected by several different parasites, including cestodes, ciliates, microsporidian, trematodes and nematodes, but thus far, the only candidate to be developed as a commercial bio-molluscicide is the nematode *Phasmarhabditis hermaphrodita* (Rae *et al*., 2007).

11.2.1 *Phasmarhabditis hermaphrodita*

Phasmarhabditis hermaphrodita is commercially available under the tradenames Nemaslug® and Slugtech® by BASF and Dudutech, respectively. The mechanism in which the nematode controls molluscs is detailed in Fig. 39.

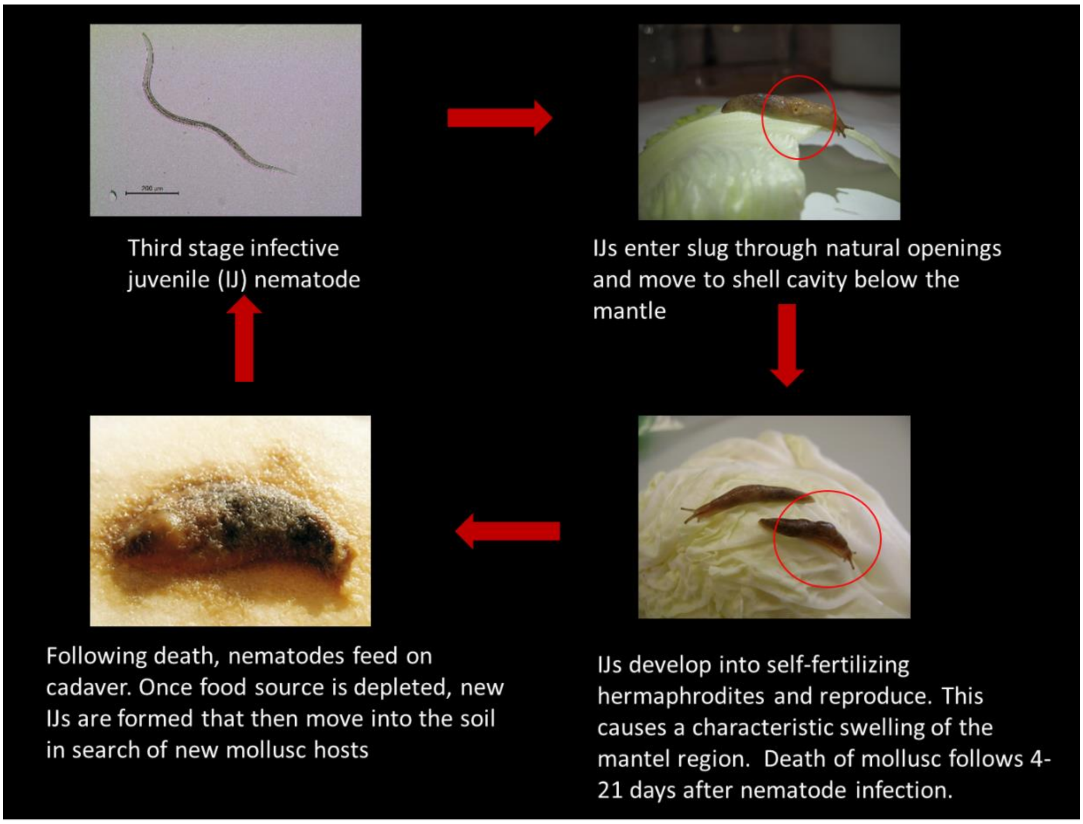


Figure 39: Mechanism in which *P. hermaphrodita* controls molluscs (Source: Author)

However, the use of nematodes as bio-molluscicides has several challenges, including the cost of production, cost of application (Approx. £110/ha), volume of water required for application, storage and shelf life of the product (Pieterse *et al.*, 2017a). Therefore, there is an array of research opportunities relating to nematodes for mollusc control.

The formulation and application of the nematode could also be enhanced. Dr Geoffrey Jaffuel, from University of Neuchâtel in Switzerland, has been working on palatable polymer-based beads to deliver the nematodes to the field, and is investigating different attractants to lure the molluscs to the beads, including sunflower oil and dead slugs.

11.2.2 New Nematode Candidates

Over the last ten years there has been a wave of researchers around the world looking at new nematode candidates for the biological control of molluscs. In the US, Dr Irma Tandingan De Ley (Fig. 40) and Dr Rory Mc Donnell have been investigating the potential of *P. californica*, *P. papillosa* and *P. hermaphrodita* to control molluscs (Tandingan De Ley *et al.*, 2014; 2016). In South Africa, Stellenbosch University PhD student, Ms Annika Pieterse, along with the author of this report, have been working on the impact of *P. papillosa* (Pieterse *et al.*, 2017b) and *P. safricana* (Ross *et al.*, 2018) on slugs. In fact, over the last 10 years there has been such an interest in this area that the total complement of the genus has grown from three species to eleven, and is continuously expanding (Ross *et al.*, 2018). In the UK, Dr Robbie Rae, from Liverpool John Moores University, has been collecting new isolates of *P. hermaphrodita* and *P. neopapillosa* across the country, in order to identify candidates with enhanced pathogenicity potential.

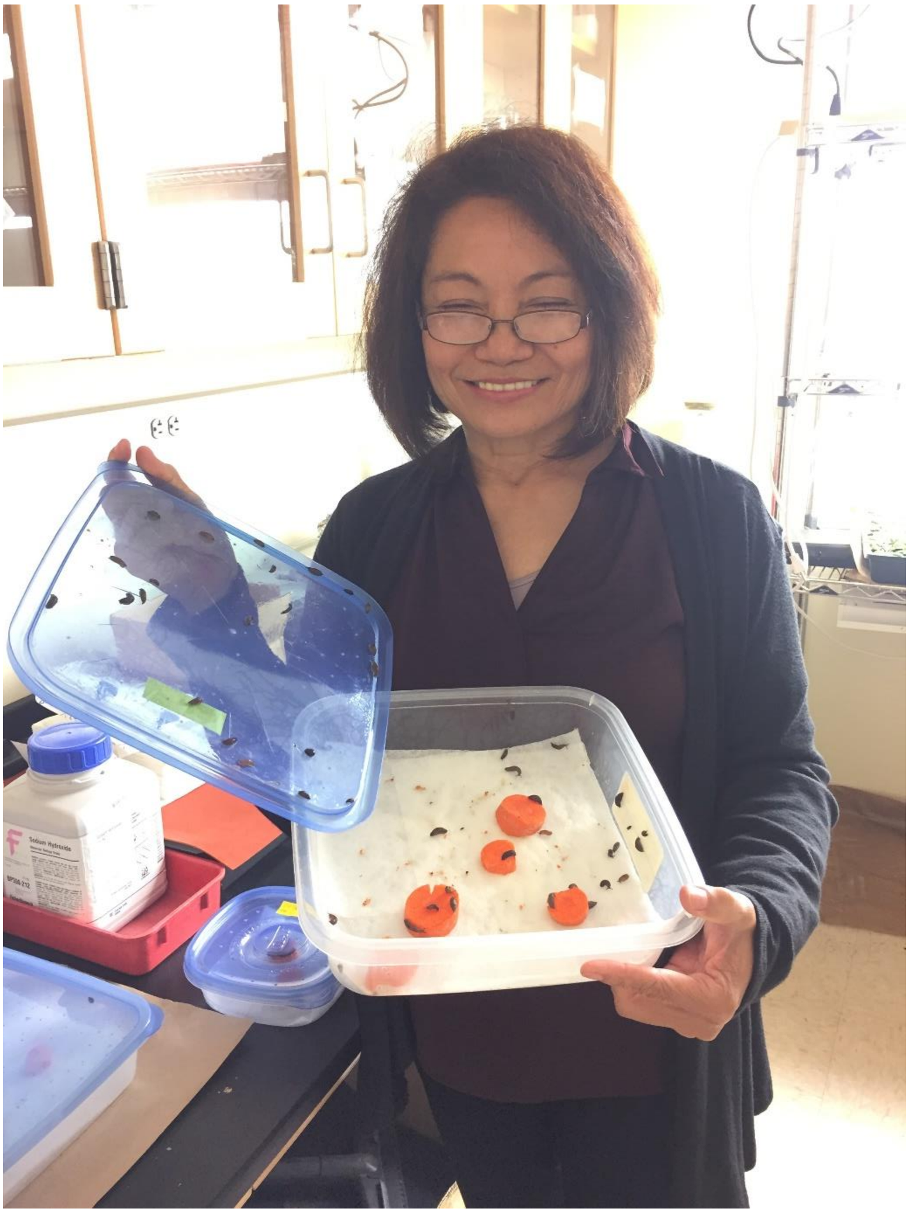


Figure 40: Dr Irma Tandingan De Ley from UC Riverside University, California (Source: Author)

However, a major challenge for new nematode candidates, (as well as the potential use of microbials), is regulation and time to market.

11.3 Chapter questions

- How do we make nematode bio-molluscicides more cost effective for broadacre crops?
- How can we reduce water usage in the application of nematode bio-molluscicides?
- Can the formulation and application of nematode bio-molluscicides be enhanced?
- How can we extend the shelf life of nematode bio-molluscicides?
- How can we speed up the registration process for all bio-molluscicides?
- Are there opportunities to develop slug control practices into a tourist attraction in the UK?
- Are there commercial opportunities for carabid beetles?

12. Next-generation Technology

12.1 RNA Interference

RNA interference (RNAi) involves a natural process in which cells turn down or suppress the activity of specific genes, because RNAi has interfered with the messengers (messenger RNA) that carry information to make a particular protein.

Recently, Monsanto has developed RNAi sprays that kill agricultural pests, and this has inspired Dr Helen Billman-Jacobe, from Melbourne University in Australia, to see what opportunity RNAi has for controlling slugs. RNAi is very specific, and Dr Billman-Jacobe was keen to investigate how RNAi could be used to disrupt reproduction or cause mortality. The idea was to develop baits containing RNAi that could be delivered orally to the slug. However, Dr Billman-Jacobe's research group have struggled to make this science a reality, and are investigating whether the RNAi remains intact, or whether enzymes present in the digestive system are able to break them down. Or maybe slugs don't have an RNAi mechanism? Dr Billman-Jacobe is open to feedback from the wider scientific community as to how this approach can be improved.

12.2 Recombinant Fusion Protein Technology

Mr Eric Gussin, from Lonza Group, says that recombinant fusion protein technology could play a role in controlling molluscs in the future. Durham University have been working on a system involving a protein carrier linked with a peptide (e.g. venom toxin), delivered orally to the molluscs.

12.3 Chapter questions

- How can the issues with RNAi research be overcome?
- Is there a commercial opportunity for RNAi and fusion protein technologies?
- What about technologies to disrupt mucus secretion or mating?

13. Agronomic Practices and Cultural Control

13.1 Risk Factors

Dr Gordon Port, from Newcastle University, highlights keys risk factors for slug damage in Table 5.

Table 5: Slug damage risk factors (Source: Dr Gordon Port)

Risk Factor	Details
Moisture	Slugs require moisture to survive
Temperature	Peak temperature for slugs is between 5°C and 20°C
Light	Slugs are most active at night, but will feed in day light on dull wet days
Soil type	Slugs prefer heavy clay soils that are difficult to cultivate, providing shelter for their survival
Crop type	Oilseed rape and vegetable crops are more susceptible to slug damage
Previous crop	Previous crops may increase the risk of slug damage
Crop residues	Reduced cultivation can increase risk of slug damage, providing undisturbed habitat for slugs

13.2 Slug Identification

Dr Rory Mc Donnell, from Oregon State University, suggests that slug identification is a key tool in choosing the right slug control method. Smaller slug species, such as *Deroceras* spp., are more susceptible, so are ideal candidates for biological control, whereas larger slug species, such as *A. vulgaris*, are less susceptible, so require a multi-tool approach to achieve control. See Rowson *et al.* (2014) for a guide to UK slug fauna (page 91).

13.3 Soil Management

Dr Gordon Port, from Newcastle University, points out that slugs are soil dwelling animals, so soil management can have a significant impact on slug numbers and behaviour.

Various studies have shown that ploughing can control slugs through mechanical damage, as well as bringing slugs and their eggs to the soil surface and exposing them to ultra violet radiation, desiccation and predators.

Generally, ploughing provides a good level of slug control, but many are moving away from this conventional method due to cost, labour requirements and impact on soil health. However, even shallow cultivation of the top 25-50mm can aid control (Spackman, 2016; AHDB, 2018).

In all cultivation methods, it is important to distribute and mix in straw, and reduce clods and cavities. It is also important to choose the right machine to produce a fine seedbed. In addition, cultivating soon after combining will remove sources of food and shelter, thus reducing slug pressure (Spackman, 2016; AHDB, 2018).

Mr Graham Potter (Fig. 41), who is a farmer from Yorkshire, has taken a strategic approach to controlling slugs. He has incorporated a combination of equipment in to his system, including the

Claydon TerraStar and Claydon stubble rake (used at night), both of which have a direct impact on disturbing the slug's environment. Mr Potter says this offers an economic method for slug control, and also helps with controlling volunteers.

Figure 41: Mr Graham Potter, farmer from Yorkshire (Source: Mr Graham Potter)

13.4 Seedbed Preparation

Seedbed preparation is a key element of slug control, with fine and consolidated seedbeds making it difficult for slugs to move through the soil profile and damage seeds. It is important that there is good soil contact with the seed to help establishment (Spackman, 2016; AHDB, 2018).

The field should be rolled after sowing to break up clods and ensure a firm seedbed.

Mr Graham Potter uses a Claydon drill in his system, but finds that it creates a furrow in the soil, making a food 'highway' for slugs, as they can easily move from seed to seed. Mr Potter has developed a double rolling methodology (Fig. 42), firstly rolling with Dalbo rollers after drilling, and then rolling again at a 90-degree angle to close up furrows and consolidate the soil, thus making it harder for slugs to move around and access the seeds.

Figure 42: Mr Graham Potters double rolling experiment (Source: Mr Graham Potter)

13.5 Drilling Depth

It is important to match drilling depth to soil type and seed-bed conditions. When drilling winter cereals into a cloddy seedbed, slug damage can be reduced by drilling at a depth of 4-5 cm (Spackman, 2016; AHDB, 2018).

13.6 Crop Establishment

In Australia, Dr Michael Nash recommends getting crops in the ground as early as possible, to get them established and past the vulnerable stage.

Mr Graham Potter builds on this by applying phosphate and nitrogen fertilisers with the seed when drilling, and trialling seed treatments. He previously compared Redigo Deter, which deters slug damage, with Vibrance Duo, which provides better root growth, control over of *Microdochium* and *Fusarium*, and rapid crop establishment, therefore getting past the susceptible slug damage stage (Fig. 43).

Figure 43: Comparison of Redigo Deter and Vibrance Duo (Source: Mr Graham Potter)

13.7 Crop Rotation

Dr Michael Nash from Melbourne, Australia, suggests that linseed is less vulnerable to slug damage, and also dries out the soil. His study found that significantly lower slug populations (mean ± SE) were observed after linseed, compared to adjacent barley fields (linseed 8 ± 3.4; barley 20 ± 7.3; T test P = 0.014, n=8) (Nash *et al*., 2016).

13.8 Cover crops

Cover crops have a key role to play in improving soil structure, organic matter and overall soil health but often provide a source of food and shelter for slugs. However, research conducted by Natural England found that cover crops did not lead to more slug numbers; however these findings have been disputed by other farmers. In addition, the study found that slugs have an aversion to mustard (Allison, 2018).

13.9 Grazing

Mr Malcolm White, a farmer from Napier, New Zealand, practices a more holistic approach to farming, and says that grazing plays a key role in crushing slugs. Dr Michael Wilson from Hamilton, New Zealand, says that high stocking rates and rotational grazing can help regulate slug populations (Wilson and Barker, 2011).

13.10 Microwave Technology

In Australia, a new component of cultural control has been developed in the form of microwave technology (Fig. 44). This technology uses thermal runaway to kill slugs, with larger slugs being more susceptible due to their increased water content. However, the technology only works if the slugs are on the soil surface, so will have limited control. Ms Svetlana Micic, from DPIRD, Albany, says that microwave technology could be a key component for controlling snails in vineyards, as the snails drop when exposed to microwaves. In addition, this technology has been shown to be effective for weed control. However, one of the main questions should be the impact of microwave technology on other organisms, especially beneficial organisms.

Figure 44: Microwave technology developed by DPIRD to control slugs (Source: Author)

13.11 Chapter Questions

- How can outputs generated from farmer led research be translated into replicable science?
- What cover crops work best at deterring slugs from the key crop?

14. Physical Barrier Control

14.1 Home Remedies

Dr Hayley Jones, from the Royal Horticultural Society, tested a number of home remedy physical barrier systems in 2018, with the aim of finding out which ones were fact, and which were fiction. The following candidates were tested:

- Copper tape (with serrated edge);
- Sharp horticultural grit;
- Pine bark mulch;
- Wool pellets;
- Egg shells; and
- No treatment.

Results showed that none of the above methods provided a superior level of slug control. Dr Jones is keen to conduct further studies on copper tape, with the aim of determining if the varnish coating present on commercial copper tapes play a role in hindering the slug control action. In California, copper fencing is used commercially by nurseries (Fig. 45).

Figure 45: Copper fence in California to control molluscs in Rosemary Christmas trees
(Source: Dr Irma Tandingan De Ley)

14.2 Schnexagon

Ms Nadine Sydow (Fig. 46), Founder of Solvoluta, has developed a new barrier system called Schnexagon. This is a paintable solution that prevents slug mucus from adhering to it. The paint contains three key components:

- Anionic;
- Non-ionic; and
- Amphoteric.

Ms Sydow points out that Schnexagon mixture is non-toxic, so will keep slugs out of your garden, but won't cause mortality, as slugs play a key role in breaking down organic matter. Schnexagon costs £20 for 375ml, which can treat 3m^2, and is certified vegan friendly.

Figure 46: Ms Nadine Sydow, Founder of Solvoluta (Source: Author)

14.3 Molluscit

Mr Mike Inglis, founder of Molluscit (Fig. 47), and Dr Andy Evans from SRUC, have developed a new barrier system that controls slugs both above and below ground. A specially designed comb element prevents slugs from accessing the plant material.

Figure 47: Molluscskit (Source: Mr Mike Inglis)

14.4 Chapter Questions

- How can barrier systems be adapted and made financially feasible for broadacre farming?
- Can barrier systems be combined with chemical, biorational, biological and/or cultural slug control options?

15. Integrated Pest Management

15.1 Integrated Pest Management Strategy

The combination of monitoring, along with chemical, biorational, biological, physical barriers and agronomic/cultural control, should be part of an integrated pest management (IPM) approach, and tailored to each farm and each individual field. This can be summarised using the slug IPM strategy pyramid in Fig. 48 and considers the eight IPM principles of the Sustainable Use Directive (Europa, 2019) and the MSG (2019) recommendations.

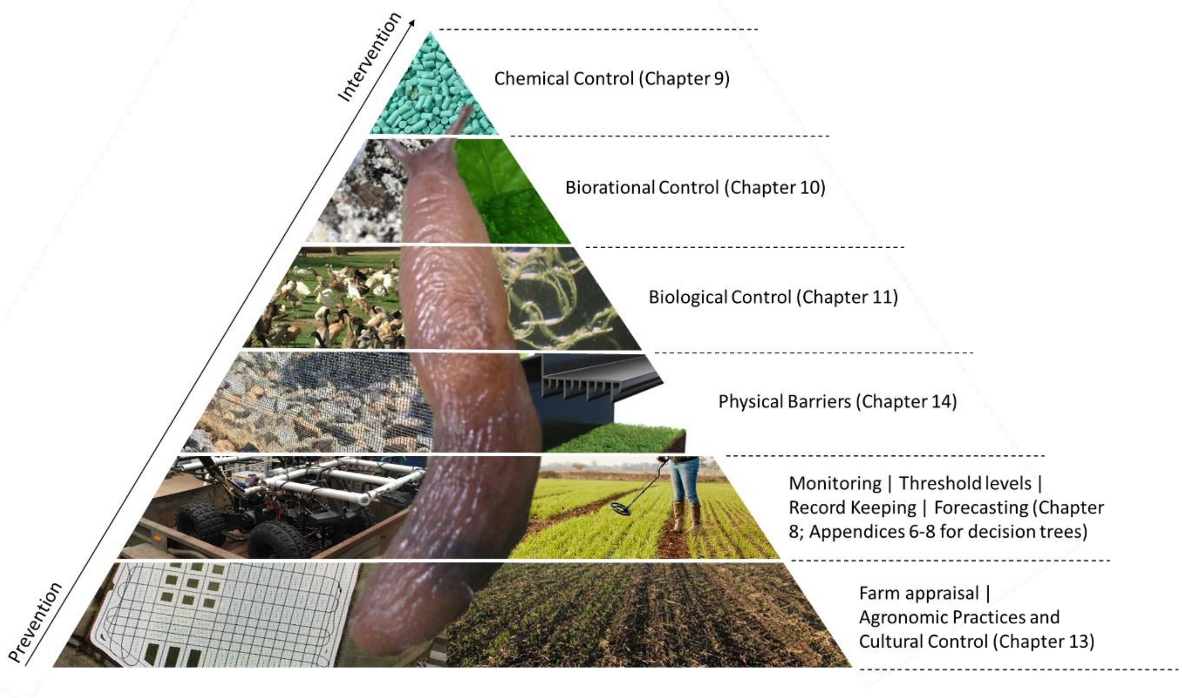


Figure 48: Slug Integrated Pest Management (IPM) Strategy Pyramid (Source: Author)

15.2 Chapter Questions

- How do we deliver a tailor-made slug IPM protocol specific to each farm and each field?
- How can farmer led research in slug IPM be promoted?
- Is there a way to digitalise the slug IPM strategy pyramid?

16. Future of Malacology

16.1 Succession Planning

Malacology, the study of molluscs, is a niche area of zoology. The average age of malacologists in the UK is around 50-60 years old, with very few young people staying in the profession due to the lack of funding and job opportunities. This is surprising considering slugs are one of the biggest pests in UK agriculture and horticulture. Unfortunately, this is posing an issue for succession planning, as many experts in this area are preparing to retire.

16.2 Development of Malacology

There is a general feeling in the UK that the development of malacology has slowed down in recent years due to lack of funding and lack of opportunities to share and develop ideas. Many farmers and growers across the world also feel they don't have access to up-to-date information on slug control.

One of the most important outputs of this Nuffield Farming scholarship was the opportunity to convene the IOBC Slug and Snail conference in Valencia, Spain (Fig. 49). This is a major milestone, as this conference has not been active since 2013. The conference brought together researchers from around the world, giving them the opportunity to present their work, network with other experts and develop project ideas that will impact the sector. The challenging part now is to access funding to keep the momentum going!

Figure 49: International Organisation for Biological and Integrated Control (IOBC) Slug and Snail conference in Valencia, Spain (Source: Author)

Another way to promote malacology is through citizen science programmes. A key output of this project was the establishment of two citizen science programmes, one in Alberta, Canada, and one in Kenya. The aim was to engage and educate local scientists and communities on the slug fauna within their gardens/farms, look at the level of slug damage and investigate methods of control (Fig. 50).

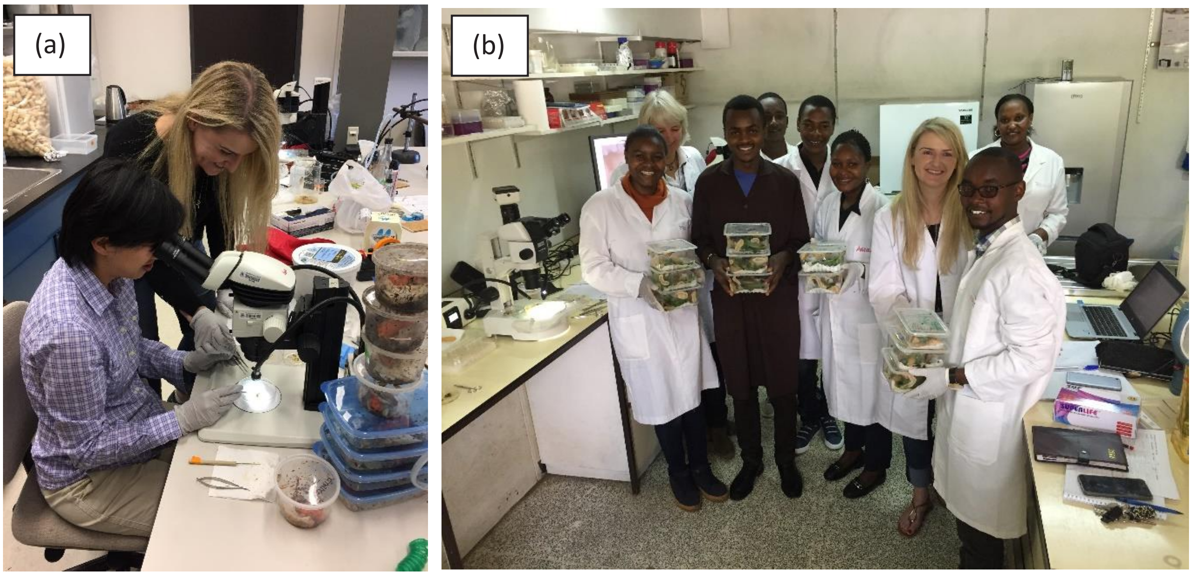


Figure 50: Dr Jenna Ross established two citizen science programmes during her Nuffield Farming travels, one in (a) Alberta, Canada, and one in (b) Kenya (Source: Author)

16.3 Chapter questions

- How can a succession plan for malacology be developed?
- How can we promote malacology to the next generation?
- How can we secure investment into malacology?
- How can we promote knowledge sharing?
- How can we encourage more citizen science programmes?
- How can we access funding to establish sustainable conferences and workshops?
- Is there an opportunity to make information on slug control more accessible to farmers and growers?

17. Novel Opportunities of Slugs

Molluscs are one of the most successful animal groups in the terrestrial ecosystem, and are major pests of agriculture and horticulture in the UK (Barker, 2001). But do they offer potential commercial opportunities?

17.1 Food and Drink Industry

Historically slugs have been used as a food source, however little is known about their nutritional value. Perhaps with supporting nutritional data, they could offer up an alternative source of protein, for either human or animal consumption.

17.2 Cosmetic Industry

The idea of using snail mucus as a beauty product dates back to 400 BC; however the concept has had a resurgence over the last few years. In Japan and other part of Asia, snail mucus has become a premium beauty product (Fig. 51).

Figure 51: Premium snail beauty products in Japan (Source: Author)

One organisation that has capitalised on this trend is Ci:z.Labo (Fig. 52) in Tokyo, Japan, where live snail facials are offered as a 'Celebrity Escargot Course' at $175 per session, with 6 sessions being recommended.

Figure 52: Ci:z.Labo in Tokyo (Source: Author)

Selfridges in London also offer an array of snail mucus products, with individual beauty mask retailing at £8.50 and above.

However, thus far, the market is primarily focused on snails, due to the already established escargot market (Heliculture), providing an easily accessible supply chain of the animals. However, slugs offer a fantastic alternative as they don't have the luxury of an exterior shell like their snail counterparts, so have evolved to have exceptional healing abilities, thus potentially making them better candidates for beauty products compared to snails. The UK is also an island infested with these animals, so the supply is plentiful, and takes the hard work out of trying to control them.

17.3 Pharmaceutical Industry

Dr Ana Rita de Toledo-Piza from Limace Biotechnologia in Sao Paulo, Brazil, has demonstrated that hydroxy-polyunsaturated fatty acids extracted from the mucus of the slug, *Phyllocaulis boraceiensis* (Fig. 53), have anti-viral properties (Toledo-Piza *et al.*, 2016; 2018).

Figure 53: *Phyllocaulis boraceiensis* has anti-viral properties (Source: Dr Ana Rita de Toledo-Piza)

Dr de Toledo-Piza (Fig. 54) has successfully used these extracts to treat a variety of viruses, including influenza, measles and herpes. Her ethos is to turn the negative impact of this agricultural pest into a positive impact for human health.

Figure 54: Dr Ana Rita de Toledo-Piza and Dr Jenna Ross in Sao Paulo, Brazil (Source: Author)

17.4 Chapter Questions

- Should the UK be commercially producing slugs rather than trying to control them?
- Do slugs offer an alternative protein source?
- Could slugs be used as animal feed protein?
- Can slug mucus be turned into a premium product for the UK beauty industry?
- Do slugs offer an opportunity to the UK pharmaceutical industry?

18. Discussion

The slug fauna of the UK is constantly evolving, with over 50% of slug species being exotic. I believe with the appropriate funding, and collaborations with organisations such as the Conchological Society of Great Britain and Ireland, Malacological Society of London, Centre for Ecology and Hydrology, AHDB and RHS, it is possible to develop a better understanding of species diversity, distribution and economic impact by conducting a systematic survey. It will also provide the UK agricultural industry with the appropriate information to make informed slug control decisions, especially relating to the Spanish slug, *A. vulgaris*.

It is also important that we prevent any further slug invasions, by introducing appropriate biosecurity measures, whereby imports can be held and inspected for the presence of exotic molluscs. This is vital, as slugs cause significant direct economic damage to crops, and can have an indirect impact on human and animal health, rejection of exported commodities and soil health. In addition, I also believe we need to develop a monetary value for this economic impact.

Regarding current slug monitoring systems, I believe they are labour intensive, with many farmers not partaking in this key practice. This means that there has been an overreliance of chemical molluscicides, such as metaldehyde, thus contributing to the negative environmental impact, and its recent controversy. I believe that it is possible to overcome this challenge by introducing mobile robotic systems which can monitor slug population in real-time, while treating slug populations simultaneously using a precision approach. With investment into this sector, this could make a massive innovative leap forward.

With the future of metaldehyde uncertain, Iron (Ferric) phosphate may end up being the only 'chemical' molluscicide option available to UK farmers and growers. This is concerning as it is likely that demand for Iron (Ferric) phosphate may exceed supply if the ban on metaldehyde is implemented. What is even more concerning is that no scientific studies have been conducted on the potential risk of developing resistance to Iron (Ferric) phosphate.

With a limited chemical toolbox, it is important, now more than ever, that research focuses on biorational, biological, physical barriers and next generation control. This includes overcoming the challenges with RNAi, as well as looking at microbials, such as bacteria, fungi and viruses. There is also fantastic scope to improve the nematode products to make them more cost effective, by utilising precision application and technologies to improve water usage, formulation and shelf life. However, considerable investment is required into the sector to make the suggested research a reality; regulatory changes will also be necessary.

Agronomic and cultural practices are also playing a more important role, especially with the shift to minimum tillage and direct drilling. This has led to a surge of farmer led research in this area, due to the demand to find an effective method of controlling slugs, combined with the decelerated development of malacology in recent years. I believe it is important that scientists work with farmers to translate these finding into scientific replicable outputs for the wider community.

The combination of monitoring, along with chemical, biorational, biological, physical barriers and agronomic/cultural control is not a new idea; however, what should be considered is combining these into a slug IPM strategy pyramid, that is tailored to each farm and each individual field.

Regarding the future of malacology, it appears that the discipline is in difficulty, with no clear succession plan in place, and limited opportunities for researchers to share and develop ideas. Therefore, we need to promote the subject to the next generation and encourage opportunities for knowledge sharing, by bringing back conferences, such as the British Crop Protection Council (BCPC) Slug and Snail meetings. One of the most important outputs of this Nuffield Farming Scholarship, was the opportunity to convene the International Organisation for Biological and Integrated Control (IOBC) Slug and Snail conference in Valencia, Spain, which brought together researchers from around the world, giving them the opportunity to present their work, network with other experts and develop project ideas that will impact the sector. This is a major milestone, as this conference has not been active since 2013. The next challenge is to access funding to keep the momentum going!

Another opportunity to promote malacology is through citizen science programmes. A key output of this Nuffield Farming Scholarship was the establishment of two citizen science programmes, one in Canada and one in Kenya, with the aim of engaging and educating local communities on slug species, damage and control.

We also need to ensure information is disseminated to UK farmers and growers, by revisiting previous work conducted by organisations, such as the AHDB, and investigating novel methods for knowledge exchange.

And finally, if slugs are so difficult to control, are we missing a trick? Should we be farming them instead and targeting slugs and their bi-products to the food, cosmetic and pharmaceutical industries?

19. Conclusions

It can be concluded that:

- Over 50% of slug species are exotic in the UK, so it is imperative that biosecurity protocols are developed to prevent further mollusc invasions;
- Slugs have a direct economic impact on crop damage, as well as an indirect impact on human and animal health, rejection of exported crops and soil health (through slug control strategies);
- There is a drive to incorporate technology into slug monitoring systems;
- With uncertainty over metaldehyde, Iron (Ferric) phosphate may be the only 'chemical' control option available in the future;
- The use of current nematode bio-molluscicides is not feasible in broadacre crops due to cost, volume of water required, storage and shelf life;
- Agronomic and cultural practices are playing an increasing role in controlling slugs, with a surge in farmer led research in this area;
- Farmers should consider a slug IPM strategy pyramid, that should be tailor-made to each field;
- The study of malacology appears to be in difficulty, with no clear succession plan in place, and limited funding available to share and develop ideas; and
- Perhaps we are missing an opportunity and we should be farming slugs instead, targeting slugs and their bi-products towards the food, cosmetic and pharmaceutical industries.

20. Recommendations

National Strategic Action:

- Conduct a systematic survey to better understand the slug fauna of the UK;
- Implement biosecurity protocols to prevent future biological invasions of exotic slugs into the UK (Appendix 3, page 80);
- Employ an eradication protocol for the Spanish slug, *A. vulgaris* (Appendix 4, page 81); and
- Make changes to regulatory system to speed up registration process for new molluscicide products.

Industry and Research Action:

- Calculate the monetary value of direct and indirect impact of slugs;
- Develop real-time mobile monitoring and treatment systems for slugs;
- Investment into the development of new and current chemical, biorational, physical barriers and biological control methods;
- Develop a system to deliver a slug IPM strategy pyramid that is tailored to each field;
- Scientists should work alongside farmer groups to translate scientific findings into practical outputs; and
- Investigate opportunities for farming slugs for the food, cosmetic and pharmaceutical industries.

Malacology Knowledge Exchange Action:

- Re-establish conference opportunities, such as the BCPC Slug and Snail meetings, and secure funding to continue the IOBC Slug and Snail conference, in order to share and develop ideas;
- Promote malacology to the next generation, and prepare succession plans to avoid the loss of key knowledge; and
- Encourage citizen science programmes in malacology to engage and educate local communities on slugs, damage and methods of control.

21. Impact of Nuffield Farming Scholarships

An overview of the countries visited and the amazing people met during my Nuffield Farming Scholarship travels can be found in Figure 55. It is fair to say that my scholarship has had a life changing impact on me, accelerating my career journey (Figure 56), and having a knock-on effect to the sector (Figure 57). I look forward to continuing this lifelong expedition, and encourage anyone reading this report to consider applying for this incredible life changing scholarship!

Figure 55: Overview of the countries and people visited as part of my Nuffield Farming Scholarship (Source: Author)

- October 2017 — •Received my Nuffield scholarship.
- March 18 — •CSC and GFP – covering the Netherlands, US, Czech Republic, Ukraine, Kenya and South Africa.
- March 18 — •Won LANTRA and CARAS awards.
- April 2018-January 2019 — •26 weeks of Nuffield travels covering US, Canada, Brazil, UK, Belgium, Norway, Kenya, South Africa, Spain, Japan, Australia and New Zealand. Established two citizen science programmes in Canada and Kenya during travels.
- July 2018 — •Received a Distinction for MBA and won Head of Business School Awards from Robert Gordon University.
- October 2018 — •Received Highly Commended from Helping it Happen Scottish Land and Estates.
- November 2018 — •Selected as Nuffield Scotland Secretary.
- January 2019 — •Started job with the UK Agri-Tech centre, Crop Health and Protection, an opportunity to drive innovation in UK agriculture, and implement Nuffield ideas for controlling slugs.
- January 2019 — •Became convenor of IOBC Slug and Snail group, an opportunity to encourage knowledge exchange in malacology.
- January 2019 — •Disseminated Nuffield findings to Sustainable Landscapes and the board of AHDB Cereals and Oilseeds.
- February 2019 — •Received a Commended from the Association of MBA's, placing me in the top five graduates in the world.
- February 2019 — •Disseminated Nuffield findings at the CARAS conference.
- February 2019 — •Winner at the Chartered Management Institute Higher Education awards.
- March 2019 — •Organised a knowledge exchange event at the Scottish Parliament, to promote the impact of Nuffield Farming scholarships in Scotland. Also organised Nuffield Scotland AGM.
- May 2019 — •Invited to Kensington Palace by Chartered Management Institute.
- June 2019 — •Organised Nuffield Scotland event at the Royal Highland Show.
- July 2019 — •Guest blogger for Centre for Agriculture and Bioscience International (CABI) on outputs of my Nuffield Farming report.
- July 2019 — •Convened the IOBC Slug and Snail conference in Valencia, Spain. This conference has not been held since 2013, but was revived after the publicity of my Nuffield Farming Scholarship.
- August 2019 — •Organised Nuffield Scotland event at Turriff Show.

Figure 56: Timeline of Nuffield Farming Scholarship (Source: Author)

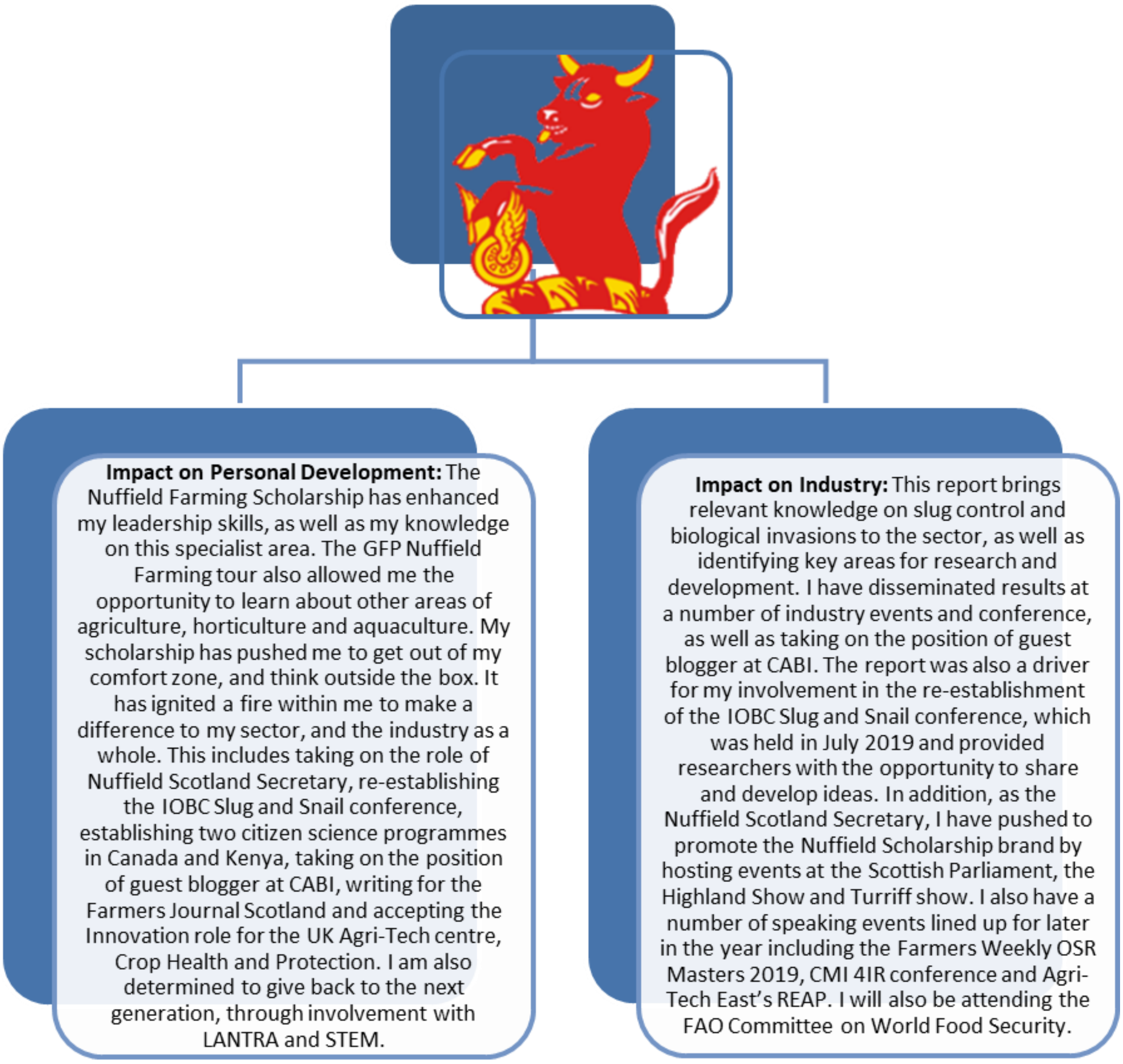


Figure 57: Impact of Nuffield Farming Scholarship (Source: Author)

22. Acknowledgements

Firstly, I would like to thank my husband and my family for their continual support during my Nuffield travels. Without their encouragement this wouldn't have been possible. I would also like to record my thanks to the staff at the Nuffield Farming Scholarship Trust, including Mrs. Christine Hill for editing my report, and to my main sponsors, the Royal Highland and Agricultural Society of Scotland, and the Agricultural and Horticultural Development Board Cereals and Oilseeds, for their support. Special thanks to Mr. Alan Laidlaw and Dr Martin Grantley-Smith for their mentorship during the process.

In addition, I would also like to thank Mr. Jan Redpath for his friendship and mentorship throughout my Nuffield journey. Jan was the only person that I trusted to read my final report before it went for review, and I know that he took the time and effort to read right to the very end.

I would also like to thank the Mains of Loirston Charitable Trust for their significant contribution towards my project, as well as the Council for Awards of Royal Agricultural Societies (CARAS), LANTRA, Robert Nicol Trust, MacRobert Trust, Rotary Club of Aboyne and Upper Deeside, Royal Northern Agricultural Society, W.N Lindsay Ltd, Lonza Group, North East of Scotland Farm Management Association, Scottish Agronomy and Aberdeen and Northern Marts.

My thanks are also due to all the contributors to this study, without which this report wouldn't have been possible. Thank you for your time, patience and amazing hospitality! This includes Dr Suzete Gomes, Mr Rildo Belarmino, Dr Ana Rita de Toledo-Piza, Mr Mike Inglis, Dr Andy Evans, Dr Solveig Haukeland, Dr Bjorn Hatteland, Dr Pamela Marrone, Dr Rory Mc Donnell, Dr Dee Denver, Dr Irma De Lay, Dr David Robinson, Mr Rod Bradshaw, Ms Kristina Polziehn, Mr Blake Vince, Dr Lothar Ott, Mr Eric Gussin, Dr Michael Wilson, Mr Allister Holmes, Mr Malcolm White, Mr Duncan Thomas, Mr Frank Collier, Mr Douglas Giles, Mr Mike Swift, Dr Stuart Davis, Mr Stewart Learmonth, Ms Svetlana Micic, Mr Andrew Slade, Dr Greg Baker, Dr Kym Perry, Dr Michael Nash, Dr Helen Billman-Jacobe, Dr Lien Luong, Dr Ziga Laznik, Dr Geoffrey Jaffuel, Dr Robbie Rae, Ms Nadine Sydow, Mr Christiaan Jansen van Rensburg, Ms Annika Pieterse, Dr David Cameron, Dr Gordon Port, Ms Samantha de Silva, Ms Amy Campbell, Dr Ben Rowson, Dr Hayley Jones, Ms Emily Forbes, Mr Graham Potter, Mr Morley Benson, Mr Francois Benne and staff at Dudutech, Vergenoegd and Ci:z.Labo.

23. Appendices

Appendix 1: Other notable Invasive Mollusc Species (Sources: Dr Suzete Gomes, Dr David Robinson and Dr Solveig Haukeland)

Contact	Information
Dr Suzete Gomes, Laboratório de Malacologia, Rio de Janeiro, Brazil	Other notable threats include *Latipes erinaceus*, *Sarasinula linguaeformis* and *S. plebeia*, the latter being a serious pest of cultivated bean (*Phaseolus vulgaris*) in Central America.
Dr David Robinson, USDA, Philadelphia, US	It is likely that global warming will make the UK more vulnerable to invasions of the Giant African snail, *Lissachatina fulica*. This would be particularly damaging, as it is known to consume over 500 varieties of plants and is ranked number 2 on the "One Hundred of the World's Worst Invasive Alien Species", funded by La Fondation TOTAL, and part of the Global Invasive Species Database.
Dr Solveig Haukeland, International Centre of Insect Physiology and Ecology in Nairobi, Kenya	Highland slug species from East Africa could also pose an invasive risk to the UK, as post-Brexit trade deals develop.

Appendix 2: Recommendations for Biosecurity Protocol in the UK (Source: Dr David Robinson and Author)

The US methodology detailed in Section 6.6 provides an ideal backbone for a biosecurity protocol for the UK. However, before this can be implemented, the following recommendations must be considered:

- Identify specialists that are active malacologists in the UK;
- Develop a centralised system of inspections;
- Develop a legal framework to allow commodities to be held for sufficient analysis time;
- Set up digital imaging protocol and incorporate molecular analysis;
- Develop a system that allows hold, action and control; and
- Collaborate between government departments, as well as government to government.

Appendix 3: Successful eradication of *Lissachatina fulica* in Florida, USA (Source: Dr David Robinson)

The Giant African Snail was introduced to Miami, FL, in 1966 by a young boy carrying three live snails in his luggage after being on holiday in Hawaii. A programme set up by the USDA and Florida Department of Agriculture and Consumer Services (FDACS), collected and destroyed approximately 18,000 snails, and by 1973, the state had successfully eradicated the snail, costing approximately $1 million. However, in 2009, a young girl from Miami was taken to hospital after showing signs of eosinophilic meningoencephalitis, also known as the "Rat lungworm disease". After interviewing the parents, it was discovered that the family were part of a religious group, whereby the young girl had taken part in a religious ritual, where the apex of live Giant African Snails had been broken and the bodily fluids had been consumed. All snails were confiscated from the group, and a search of the immediate surroundings was conducted. However, in September 2011, the USDA confirmed the presence of the Giant African Snail in Miami, close to the previous site. In response, surveys were conducted throughout southern Florida, and the USDA provided funding to help eradicate this pest. Specially trained sniffer dogs were brought in to assist the project, and a community outreach programme was set up, and included TV, radio, newspapers, snail blogs, billboards and a school outreach campaign. A Giant African Land Snail Junior Detective scheme was set up, whereby 5th grader children in the Miami-Dade County could join as a Junior Detective, and along with their parents, look for and report sightings of the snail, in exchange for their sheriff badge. As of 1st June 2018, over 168,300 snails, from 719 sites, have been collected and destroyed. The aim is for complete eradication within the next 2-3 years.

Appendix 4: Recommendations for eradication *Arion vulgaris* in the UK (Source: Author)

Controlling successful invasions of molluscs can be a significant challenge, but this is something that the UK must consider for the Spanish slug, *A. vulgaris.* Following on from Section 6.7, it is recommended that a similar programme be setup to eradicate *A. vulgaris* in the UK. This could be achieved by:

- Establishing a Spanish slug task force;
- Training specialist dogs to identify the Spanish slug. Specialist dogs can be train to species level;
- Increasing public awareness of this slug (e.g. TV, radio, newspaper articles and billboards);
- Establishing a community outreach programme, similar to the Giant African Land Snail Junior Detective scheme used in Florida;
- Using the AHDB platform to better inform farmers; and
- Using the RHS to better inform gardeners.

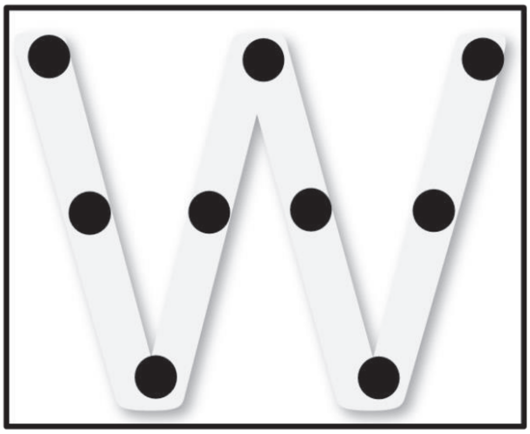
Appendix 5: Current Monitoring Systems (Source: AHDB, 2018)

Risk to crops is usually determined using monitoring systems to estimate the population size of slugs. Monitoring is a key tool in avoiding unnecessary prophylactic applications of chemical molluscicides, and is a key component of the integrated pest management approach discussed in Chapter 15. Historically, monitoring has involved:

- Using refuge traps (e.g. plant pot saucer);
- Trapping in mild and wet weather (5-25°C);
- Trapping in previous crops or soon after harvest;
- Timing based on crop type:

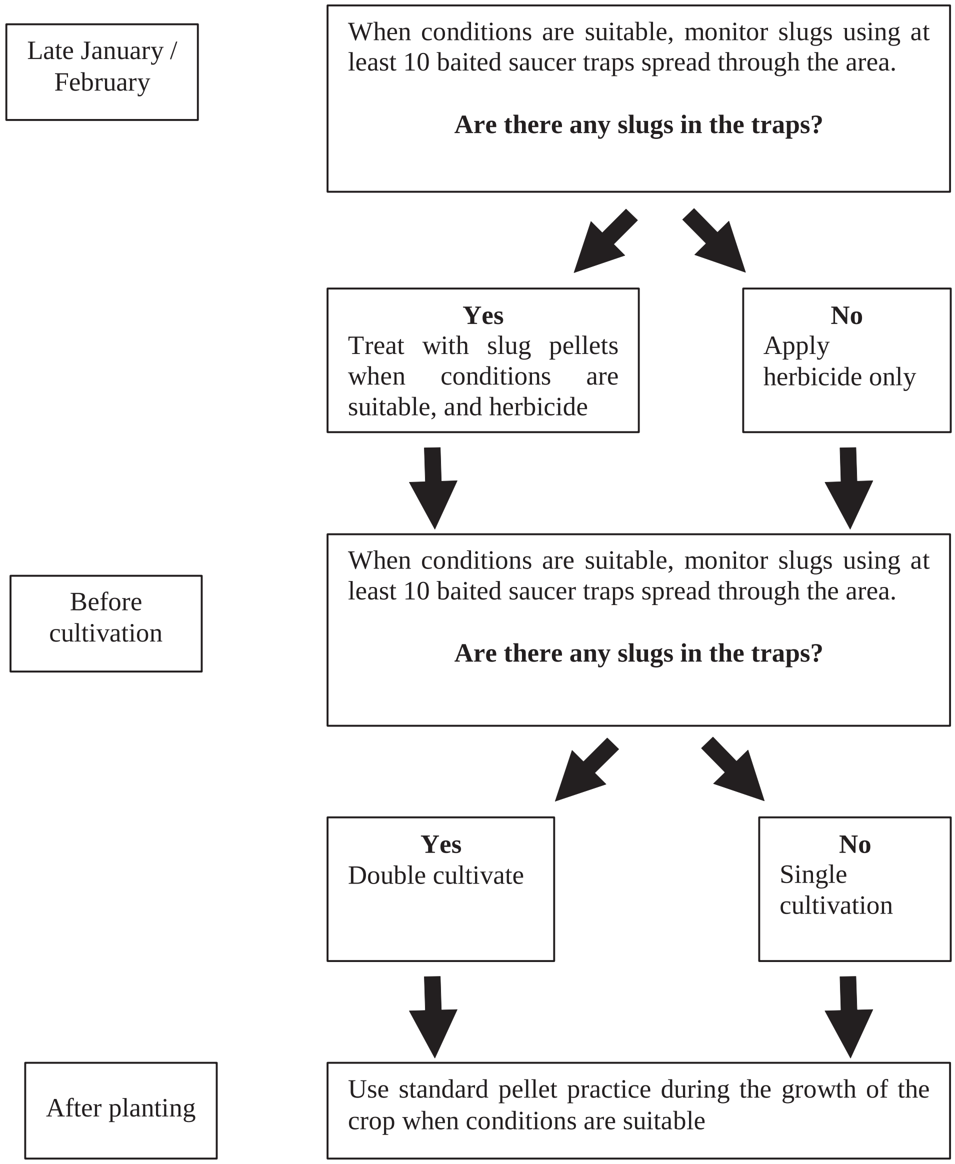
Crop Type	Timing of Monitoring
Winter cereal	Sowing through to first tillering (GS21), however monitoring should continue through winter
Oilseed rape	Sowing through to first true leaf stage
Potatoes	At 50-75% canopy closure, and again at early stages of tuber bulking
Field vegetables	Lettuce (January/February); Brussels sprouts (March/April)

- Baiting using 20mls chickens' layers mesh or cereal grain-based food;
- Positioning nine traps in a 'W' shape (see (13 traps in fields larger than 20 ha);
- Placing traps at the side of tramlines with a marker cane;
- Examining traps early the next morning;
- Counting the number of slugs in each trip; and
- Comparing counts to threshold levels, and taking appropriate action where required:

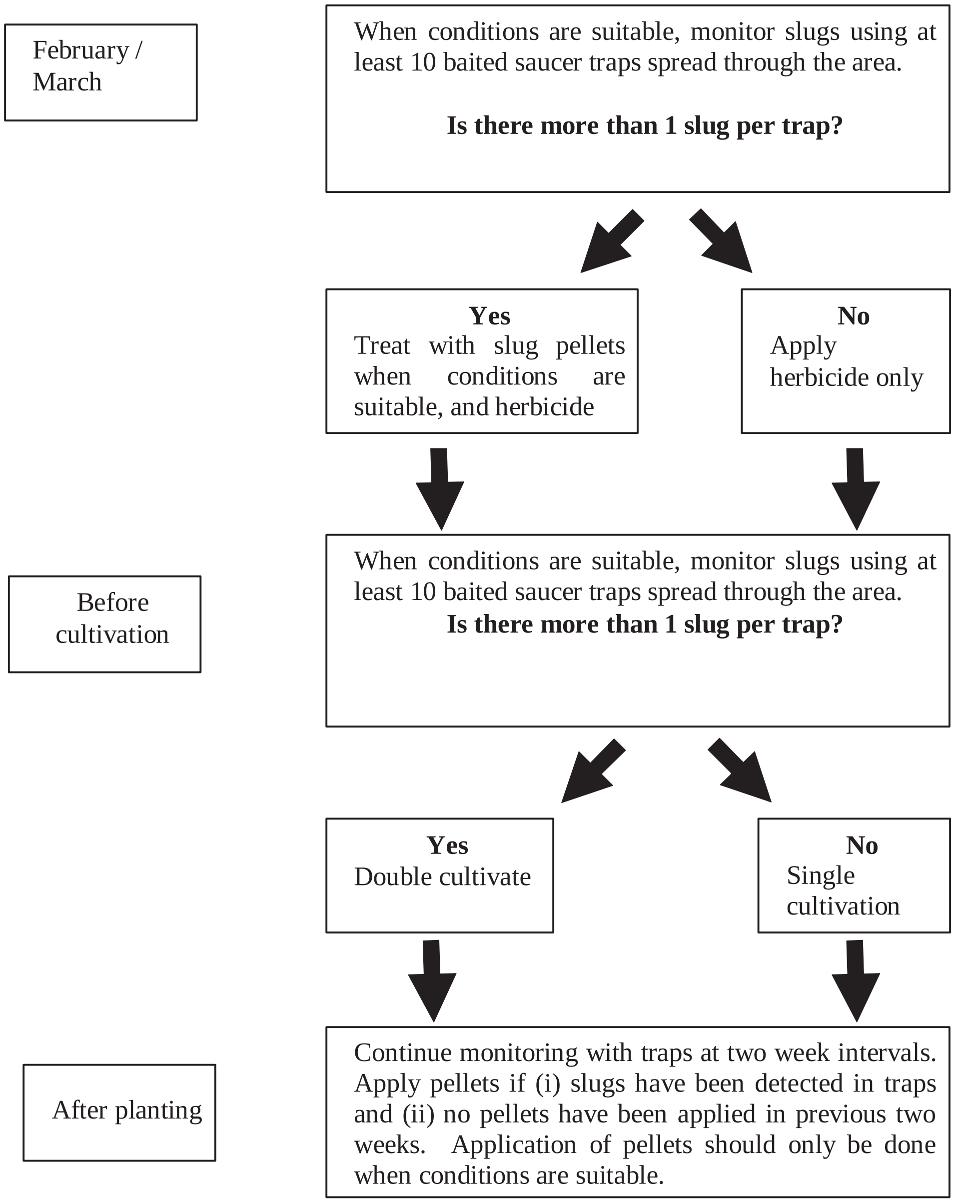


Crop Type	Threshold (average number of slugs per trap)
Winter cereal	4
Oilseed rape (Standing crops)	4
Oilseed rape (cereal stubble)	1
Potatoes	1
Field vegetables	1

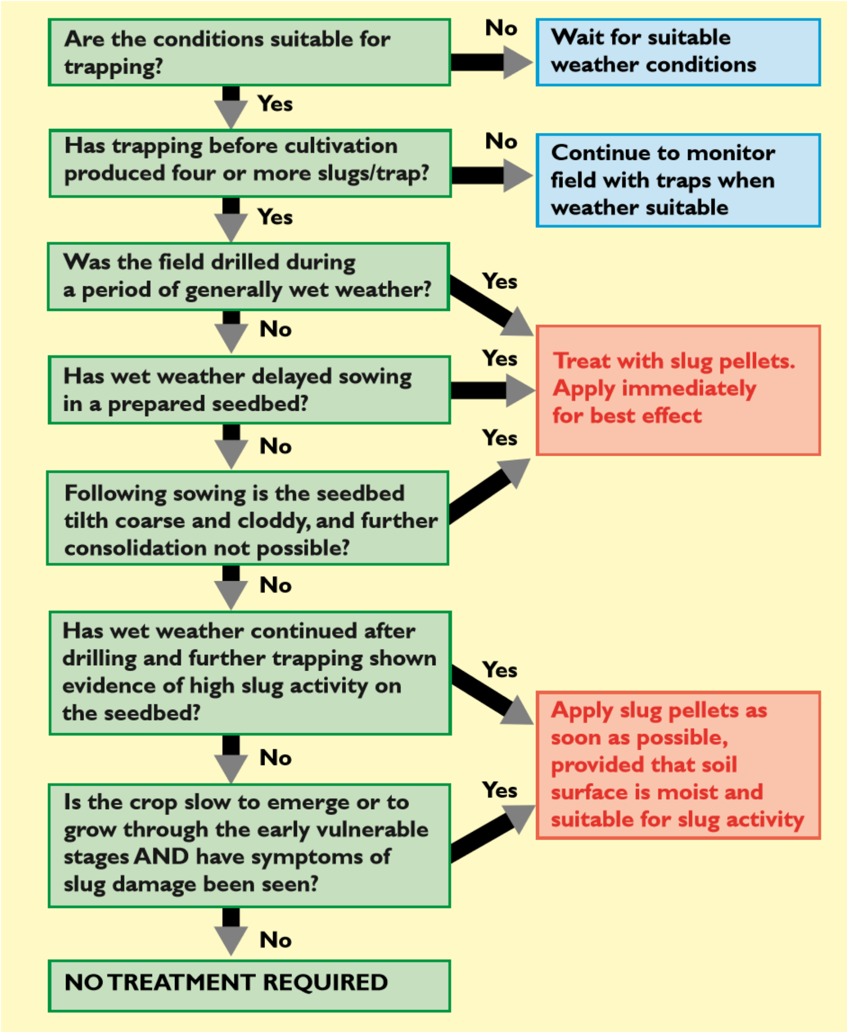
Appendix 6: Decision tree for Lettuce crops (Source: Dr Gordon Port)



Appendix 7: Decisions tree for Brussels sprout crops (Source: Dr Gordon Port)



Appendix 8: Decision tree for Winter Wheat crop (Source: Dr Gordon Port)



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