Introduction of biological control agents against the European earwig (*Forficula auricularia*) on the Falkland Islands

N. Maczey[1], D. Moore[1], P. González-Moreno[1] and N. Rendell[2]

[1]*CABI, Bakeham Lane, Egham, Surrey, TW20 9TY, UK. <n.maczey@cabi.org>.* [2]*Falkland Islands Government, Environmental Planning Department, P.O. Box 611, Stanley, Falkland Islands.*

Abstract The Falkland Islands (FI), as with many island ecosystems, is vulnerable to invasive species, which can cause wide ranging social and environmental consequences. Control of invasive species is widely recognised as a priority, but there have never been attempts to use classical biological control (CBC) for this purpose in FI. The European earwig was recently introduced to the FI and has since become abundant in the Stanley area and some other settlements on the islands. Earwigs now cause considerable damage to garden crops and also pose a number of health hazards. There are also concerns that earwigs have started to spread into grasslands and irreversibly alter this important native ecosystem. After extensive stakeholder consultations it was decided to use the invasive earwigs as a case study for the introduction of CBC to the FI. Based on previous work on earwig control, supplemented by additional host range testing, two tachinid flies, *Triarthria setipennis* and *Ocytata pallipes*, were selected as the most suitable control agents for the Falkland Islands. Extensive awareness raising activities, focusing on the threat of invasive species, benefits and risks of CBC, secured the support of the wider public to go ahead with the release of both control agents during 2015 and 2016. Major challenges encountered during the release process were the need to install makeshift quarantine facilities and the switchover of the life-cycle of both control agents to southern hemisphere seasons.

Keywords: awareness raising, invasive species, *Ocytata pallipes*, tachinid flies, *Triarthria setipennis,* UK Overseas Territories

INTRODUCTION

The European earwig, (*Forficula auricularia*, Order Dermaptera) is widely regarded as a beneficial predator of insect pests in fruit orchards within its native range of Europe and West Asia (Nicholas, et al., 2005; Dib, et al., 2010), however outside this range there are reports that this species can cause significant agricultural problems (Kuhlmann, et al., 2001). In 1997/1998 the European earwig was reliably recorded for the first time in the Falkland Islands (FI), an archipelago in the South Atlantic Ocean, around 500 km off the southern Patagonian coast of South America. Since then the earwig has become a significant pest on the islands causing damage to garden and greenhouse plants and leading to a halt in the production of a number of commercial crops (Maczey, et al., 2012). The earwigs are also posing a number of health hazards, particularly in autumn (March/April) when they invade buildings in large numbers. They have been found in asthma inhalers and beneath the seals of oxygen masks causing the local hospital to introduce additional safety procedures checking equipment for the presence of earwigs prior to use. Many households currently spend substantial amounts of money to control earwigs primarily by having the foundations of their houses sprayed with pesticides once or twice a year. Since its introduction the earwig has become common in the Stanley area and a number of settlements in the wider countryside. There is also concern they may spread into native grasslands, with a risk of irreversibly altering the indigenous ecosystem posing a particular threat to a high number of endemic arthropods (Maczey, et al., 2012).

Classical biological control (CBC) has the potential to offer effective, economic and sustainable control of this invasive species. This method involves the deliberate release of specialist natural enemies – mainly insects and fungi – from the invasive's native range. The aim is to reduce the abundance of problem species in its introduced range below an ecological or economic threshold. The European earwig is a promising target species for CBC on the FI, particularly as chemical sprays are ineffective, and because of its great mobility (Santini & Caroli, 1992). Off the shelf solutions using parasitoid tachinid flies from Europe, including Great Britain, are feasible. One such species *Triarthria setipennis* has established successfully in British Columbia and Newfoundland where studies have indicated a considerable reduction in earwig numbers, most probably due to high levels of parasitism in the mid-1970s (Morris, 1984). However, since 1978, no further evaluation of parasitoid impact has been undertaken. A second species of parasitoid, *Ocytata pallipes*, was introduced into Canada to control the European earwig during the 1990s but no monitoring took place and establishment is unknown (Kuhlman, et al., 2001). *Ocytata pallipes* and *T. setipennis* have also been introduced into the USA as early as the 1920s (Oregon) and also into New Zealand (Kuhlman, et al., 2001). Again, little is known about the success of these releases.

During a workshop in Stanley in March 2012 there was consensus on the feasibility of biological control of invasive non-native species on the South Atlantic UK Overseas Territories and that the European earwig would be a target well suited for CBC in the FI. Experts working on invasive species on the FI and also members of the general public saw an urgent need for sustainable control of this species. Equally, the Government of South Georgia saw this as an opportunity to reduce the risk of future introductions of earwigs to South Georgia. The Falkland Island Government (FIG) therefore decided to commission a host range testing programme to assess the safety and suitability of two parasitoid flies, believed to be host specific to the European earwig, for introduction into the FI (Maczey, et al., 2016).

No native earwig species inhabit the FI, therefore host range tests were conducted on insect species (crickets and cockroaches) representing insect orders which are closely related to earwigs. The Falklands have one native species of cricket, the camel cricket (*Parudenus falklandicus*). The results showed that there was no indication that either of the two assessed fly species (*O. pallipes* and *T. setipennis*) can develop or otherwise impact on the viability of any of the test species, even when artificially forced to ingest parasitoid eggs or inoculated with fly larvae, which would rarely happen under natural conditions (Maczey, et al., 2016). The tests confirmed our opinion that there would be

In: C.R. Veitch, M.N. Clout, A.R. Martin, J.C. Russell and C.J. West (eds.) (2019). Island invasives: scaling up to meet the challenge, pp. 389–393. Occasional Paper SSC no. 62. Gland, Switzerland: IUCN.

no risks to non-target species if one or both of these highly earwig-specific tachinid fly species were released on the FI (Maczey, et al., 2016).

Based on the results from the host range testing, the Environmental Committee and Executive Council of the FIG decided to go ahead with the release of both agents, provided there was sufficient support from the wider public. Up until this point stakeholder acceptance for the introduction of a new species into the FI had not been assessed and the Environmental Committee decided to conduct a range of awareness raising activities to encourage residents to voice their concerns and engage in open discussion on the safety and scope of CBC of earwigs. This paper covers both the outcomes of the awareness raising activities and the results of the subsequent release of the control agents conducted between 2015 and 2017.

MATERIALS AND METHODS

Stakeholder consultation

We wanted to engage with the residents of the FI to understand whether biological control, in general, and the release of two parasitoid fly species, in particular, was of any concern or would be largely welcomed by the general public and/or experts and scientists working in conservation or agriculture on the FI.

At the core of all consultations with stakeholders we communicated four major premises:

- The release of the control agents is safe and does not pose any risks for native species, human health or food production, in contrast to the current use of large quantities of a highly toxic pesticide (Demand® CS).
- Costs for release would largely be covered through secured funding from Defra (Darwin Initiative).
- Although we saw no major hurdles for a successful establishment of both fly species, establishment can never be guaranteed, and this could be a reason for failure.
- Equally, if successful establishment has taken place, the amount of control exerted by the released agents is difficult to predict. Although in the absence of hyperparasitoids (in this case parasitic wasps known to develop inside the pupal stage of the tachinid flies) the likelihood for a good control is high, this is something which cannot be predicted with absolute certainty.

Stakeholder consultation regarding the biological control of earwigs focused on three main steps:

Providing initial background information

Information explaining the principles of biological control and the safety testing of the proposed control agents, including a 'frequently answered questions' (FAQ) section, was made available on the FIG website. In addition, a two-page flyer providing information on our work was distributed throughout Stanley prior to any public events.

Advertising opportunities to get more detailed information and voice any concerns

Website and flyer announcements were made of the dates for presentations and opportunities for open discussions. The documents also gave contact e-mails to arrange meetings or discussions outside these dates or to voice any concerns via e-mail. Times and locations for all events were also broadcasted by radio and announced in the local newspaper. An invitation to add to the FAQ was also given on the website. Presentations given – one broadcasted by local TV – also included invitations to forward any questions or concerns to the project team.

To present CABI's work on earwig control and engage with the public

Aside from the widely advertised events, discussions with residents took place on many other occasions. These included meetings with pest controllers, members of the legislative assembly (MLAs), scientists from government departments and NGOs, teachers, commercial growers and farmers. Discussions continued after FIG was confident enough that it would have the backing of the public for the release of the control agents throughout the length of the project and also included direct demonstrations of the activities at the release facilities.

Release programme

In the native range, rates of parasitism by *T. setipennis* and *O. pallipes* vary considerably between meta-populations of earwigs, and large numbers of the host need to be collected to obtain sufficient parasitoids for release and establishment. There are no estimates of how many individuals need to be released to achieve the formation of a parasitoid population in a new environment, but as a general rule the more individuals are released the better the chances are for establishment.

Trapping of earwigs took place in orchards in England during 2015 and 2016. Sites selected for collecting focused on locations combining ease of access with high numbers of specimens, both of earwigs and parasitoids likely to be obtained. Trapping involved installing flowerpots, 10 x 10 x 17 cm, filled with egg cartons, into trees 1 to 2 m above ground. Distribution of traps and the collecting regime are given in Table 1. Earwigs were collected at roughly monthly intervals three times per year.

Collected earwigs were kept in 40l plastic containers, housing no more than an estimated 2,500 earwigs per container. Egg cartons were used to provide hiding places and lids were fitted with netted openings to give sufficient aeration. The edges of containers were covered with

Table 1 Earwig/parasitoid collecting regime.

Site	No. of traps 2015	No. of traps 2016	Setup date 2015	Setup date 2016	Collecting period 2015	Collecting period 2016
Silwood Park, Berkshire	43	31	29/6/15	27/5/16	29/7/15 – 29/9/15	26/7/16 – 21/9/16
South Darenth, Kent	230	200	03/7/15	25/5/16	28/7/15 – 10/9/15	15/7/16 – 20/9/16
East Malling Research, Kent (EMR)	300	325	13/7/15	01/6/16	5/8/15 – 25/9/15	11/7/16 – 16/9/16
Target Farm, Marden, Kent	-	160	-	23/5/16	-	13/7/16 – 20/9/16

Fluon® to prevent earwigs escaping. Food consisted of a mixture of vegetables (lettuce and carrots) and dry dog food applied three times a week. The earwigs were kept for a period of six to eight weeks and, afterwards, when the majority of parasitoid larvae had left their hosts, were released back at the trapping sites.

Earwig cultures in the lab were checked for parasitoid pupae three times a week. Pupae were separated to species and stored in glass tubes sealed with a mesh cover to allow aeration whilst preventing any potential hyperparasitoids from escaping (Fig. 1). The tubes were then placed inside a larger plastic container with a meshed opening to allow for aeration. Inside this plastic container moistened tissue facilitated high humidity to prevent desiccation of the pupae.

In 2015 all pupae were stored at 16˚C until mid-September, afterwards *O. pallipes* at 12˚C and *T. setipennis* at 8–10˚C until their shipment to Stanley in November 2015. In 2016, pupae of *O. pallipes* were stored at 10–12˚C. At this temperature hatching was delayed long enough to allow two separate shipments to Stanley in August and September. Pupae of *T. setipennis*, which hibernates in this stage, were stored at room temperature (18–20˚C) to mimic natural conditions. From October onwards, the pupae of *T. setipennis* were kept at 10˚C to simulate more natural overwintering conditions.

On arrival at Stanley, sealed storage boxes containing vials with pupae were stored in a specifically developed quarantine shed (details provided at: <http://www.darwininitiative.org.uk/project/DPLUS033/>) and kept at 20˚C to trigger hatching. Quarantine facilities were used as a safety precaution in case hyperparasitoids had contaminated the fly cultures. Hatched flies were transferred into rearing tents located in a polytunnel on a daily basis. *O. pallipes* were kept there for mating and depositing of micro-eggs on carrot pieces previously exposed to earwigs, so that they had obtained the scent of the host species. The carrot pieces contaminated with fly eggs were then fed to locally collected earwigs. After inspection confirmed that most fly eggs had been ingested by earwigs, these were released at sheltered locations in Stanley with high densities of earwigs. Adult flies of *T. setipennis* were kept only 4–5 days in rearing tents, to allow mating, after which they were released at sheltered locations with high host densities.

Fig. 1 Pupae of *T. setipennis* inside their storage containers.

RESULTS

Stakeholder consultation

Attendance of public events varied from only three visitors on one occasion to up to 30 visitors during the demonstration of the release facilities. Feedback after presentations centred on the safety of CBC. Most frequent questions were: whether the release control agents could replace one nuisance species with a second one; or what the flies would feed on once earwigs went down in numbers. Our impression was that within the attending audience it was relatively straightforward to dispel such concerns by explaining in more detail the host specificity and dependence of the control agents on host density levels and that CBC will not lead to complete eradication of the target species.

People were relieved when seeing the small size of pinned specimens of the agents passed around, having expected something much larger. Worries about flies invading buildings could be dispelled by pointing out that these species, in contrast to house flies and other species, will not actively be attracted to houses. Some gardeners worried that eggs or larvae of the biological control flies would end up on vegetables; although not being a health hazard in any way this was seen as unpleasant. The answer to this was that the flies will deposit eggs and larvae only on items already smelling strongly of earwigs and in the case of food items these would be already heavily damaged crops beyond consideration for human consumption.

Repeatedly, residents raised general concerns about the continued use of pesticides. Worries about the build-up of resistance, has already led to changed usage of different products. There were also concerns that spraying may temporarily reduce earwig densities to a satisfactory level which in turn could result in diminished support for CBC. However, most residents seemed to be aware of natural fluctuations and also that earwig numbers would be likely to increase when the use of pesticides is reduced. Several times the decline in native 'black beetles' (a species of rove beetle, Staphylinidae) was pointed out, which was also attributed to the use of pesticides. The loss of native 'black beetles' was mostly regretted but on occasion the intrusion of insects of any kind into buildings was seen as undesirable. On occasion it was suspected that the decline of native species was caused by the earwigs themselves and related to a scarceness of such species in areas with high earwig densities.

Frequently, people had questions about possible obstacles to the establishment of the control agents. Comments were made on the possible impact the current use of pesticides may have on the establishment and efficacy of the control agents. Pesticides are mostly applied in autumn when the *T. setipennis* will only be present as dormant pupae. However, spraying may still have some impact on the *O. pallipes*, which overwinters as larvae inside living earwigs. Given the climatic conditions on the FI the majority of earwigs will still overwinter outside and therefore escape pesticides. We expect that as the flies begin to establish and gradually start to control the population of earwigs in Stanley the need for spraying will reduce so impacting less on both earwigs and flies. There was also concern about the availability of flowers providing pollen and nectar for adult flies, something we believe is not a problem during the time period when adult flies occur during late spring and summer. Generally, the audience was also keen to reconstruct the history of earwig introduction with various speculations on time and entry points being discussed. There was general agreement that the biological control will support a reduction in demand for chemical treatment both reducing costs and risks for human health and the environment.

Release programme

During 2015, an estimated 50,000 earwigs were collected in the UK. In 2016 numbers dropped to 18,500 earwigs despite an increase of traps from 573 to 716. Earwig densities peaked in mid-August with the majority collected up to this time still being larvae. In each year, numbers dropped considerably until the end of the collecting period at the end of September.

A total of 147 pupae of *T. setipennis* and 237 of *O. pallipes* were obtained from the earwigs up to 28 October 2015. Discounting prematurely hatched flies, altogether 145 pupae of *T. setipennis* and 212 of *O. pallipes* were shipped to Stanley for a first release trial on the Falkland Islands in November 2015. In 2016, 358 pupae of *T. setipennis* and 284 of *O. pallipes* were collected until 21 December. Discounting prematurely hatched flies, a total of 256 pupae of *T. setipennis* were shipped to Stanley in January 2017, and 225 of *O. pallipes* in August and September 2016. A breakdown of collected parasitoids per site and estimated parasitism rates is given in Table 2.

In November 2015, hatching rates of *O. pallipes* at quarantine facilities in the FI were poor, with all flies dying shortly after emergence. The most likely cause for this was the prolonged storage of fly pupae under cold conditions prior to the release, which aimed to synchronise hatching with the onset of summer in the southern hemisphere. At the same time *T. setipennis* did not hatch at all and emergence only started in January/February 2016. Only a few flies hatched over several weeks, which were kept in the mating tents (Fig. 2) and, after six days, altogether only 15 flies were released into an open polytunnel containing high densities of earwigs.

Shortened storage periods for *O. pallipes* and prolonged hibernation of *T. setipennis* allowed a significantly improved hatching rate in 2016. More than 200 *O. pallipes* hatched in August and September 2016. They mated and subsequently deposited a large number of micro-eggs on carrot pieces which had previously been exposed to earwigs. 1,800 earwigs collected locally were then fed with pieces of carrots contaminated with fly eggs and released in Stanley in October. From 256 pupae of *T. setipennis* transported to Stanley in January 2017, 185 flies hatched during February. Some flies died within a short period after hatching, but a large proportion were released into sheltered places in Stanley.

Fig. 2 Dave Moore demonstrating the fly rearing tents during open day at Government House gardens, Stanley in Nov. 2015 (photo: Sharon Jaffray, Penguin News).

DISCUSSION

Stakeholder consultation

This was the first introduction of a non-native species for the control of an invasive species on the FI, and a certain level of concern from expert stakeholders and the general public was anticipated. Therefore, we tried to encourage residents to voice their concerns and engage in open discussion on the safety and scope of CBC. At the core of all consultations were these premises:

The release of the control agents is safe and does not pose any risks for native species, human health or food production

Both successful establishment of CBC agents and the amount of control they can exert can never be guaranteed and these can be a reason for failure.

The general feedback most people gave was that of cautious optimism and being in favour for biological control provided it is safe. It was important for most people to have the assurance that biological control does not lead to the introduction of a species which could become problematic. We believed that through in-depth discussions worries and concerns could largely be dispelled. People became willing to trial a release hoping that it would provide the anticipated long-term solution to the earwig problem, whilst being fully aware that there remains a certain risk of failure. However, this was only partly driven by direct support of CBC versus an equal measure of concern about risks and side-effects associated with the current use of toxic pesticides.

Compared to the amount of advertising preceding public events, the overall turnout was ~1% of the population of

Table 2 Earwigs, parasitoids and % parasitism recorded in 2015 and 2016.

Site/orchard	Year	Earwigs collected	*T. setipennis*	*O. pallipes*	% parasitism *T. setipennis*	% parasitism *O. pallipes*
Darenth	2015	3,000	16	3	0.5	0.1
Darenth	2016	2,800	49	6	1.8	0.2
Silwood	2015	1,000	6	0	0.6	0.0
Silwood	2016	950	52	8	5.5	0.8
EMR total	2015	46,000	125	234	0.3	0.5
EMR total	2016	10,300	149	234	1.4	2.3
Target farm	2016	4,250	108	36	2.5	0.8

the Falklands and thus relatively low (although one might consider drawing in 1,000 attendees in four events in a large town of 100,000 a very good turnout). Attendance during the first open day at the release facilities was (~30 visitors) comparably high and attracted the attention of local radio and television. However, this dropped significantly in the second release year, going down to just a handful of visitors. The same was true for other types of engagement towards the end of the project. Once initial concerns were dispelled there was increasingly less new information between individual events, both from the side of release activities and any residual concerns to be shared. This may have resulted in a declining interest or possible increasing acceptance by the public over time compared to the start of the project.

Release programme

Despite intensified efforts, earwig trapping in England during 2016 yielded less than half the numbers of earwigs obtained in the previous year, which was mainly due to a drastic population crash in a single cherry orchard at East Malling Research. In addition, earwig densities at Target farm varied strongly throughout the year with few earwigs being collected in September. Low earwig numbers in 2016 were offset by a recovery of parasitoid populations, which had been very low in 2015. In both years the quantity of *T. setipennis* pupae collected was substantially lower compared to 1,000+ pupae collected from 20,000 earwigs in 2013 when the host range testing took place (Maczey, et al., 2016). It remains unclear whether *T. setipennis* suffered a population crash in 2015 or if the collecting sites chosen in 2015/2016 were more generally characterised by low rates of parasitism. Studies in continental Europe recorded, on average, higher rates of parasitism for this species (Kuhlmann, 1995). In both years, although a few individuals emerged very early in the season, most *T. setipennis* pupae were found from the beginning of September onwards. This coincides with field observations of some pupae very early in the season in England indicating a more pronounced second generation compared to its phenology on the continent, where occurrence of pupae peaks in August (Kuhlmann, 1991). Collecting earlier would not have yielded more pupae for release though, as these mostly emerged early without a hibernation period, far too early for a release in the FI.

The low number of collected parasitoids and a low hatching rate in Stanley in 2015 was not sufficient to enable establishment of either of the two species. One major problem was switching the lifecycle from a northern hemisphere rhythm to the seasons in the FI. The lack of synchronisation of life cycles between the northern and southern hemisphere is a well-documented problem in biological control (Waterhouse & Sands, 2001; De Clerck-Floate et al., 2008). *Ocytata pallipes* normally remains in the pupal stage only for a short period and initially we tried to delay hatching until the Falkland summer through storage at lower temperatures, hoping to slow down development. However, the species does not tolerate being stored for long periods at low temperatures resulting in poor survival rates. In 2016, this was addressed by shipping pupae of *O. pallipes* to Stanley several times between August and October. Release in Stanley during late winter relied on creating a suitable local environment to allow it to parasitise earwigs soon after arrival. Therefore, flies were kept in an artificially heated polytunnel warm enough to allow both earwigs and flies to be active during the winter months.

The first release trial for *T. setipennis* also failed but for a different reason. November was too early to break the dormancy of this species, which hibernates in the pupal stage, and early exposure to elevated temperatures (20°C) only led to unsynchronised emergence in January/February. For the second release, pupae were kept at low temperatures until mid-January. This resulted in a much better synchronised hatching whilst still allowing a sufficiently long period during the summer in the FI for the completion of a full life-cycle.

The adapted methodology led to much improved results and both fly species were successfully released, albeit with lower numbers than initially hoped for. For *O. pallipes*, this was mitigated in 2016 by keeping hatched flies initially in cages up to the point of eggs being deposited and releasing larger numbers of earwigs fed with contaminated pieces of carrots. The ecology of *T. setipennis* does not allow a similar approach, but for this species hatching rates had strongly improved compared to the previous year and the chances for mating were increased by keeping this species caged for six days before the release.

At this stage of the release programme we do not know whether either or both fly species have established. If establishment has been successful, it is still far too early to observe an impact on earwig numbers and this will only become apparent during future years.

ACKNOWLEDGEMENTS

We would like to thank Jeremy Poncet for his immense contributions to the project. A big thank you goes also to the residents of FI for their support. Funding for this project was provided by FIG and the Darwin Initiative (Darwin+).

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