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Host testing, establishment and biology of the gorse soft shoot moth, *Agonopterix umbellana* (Fabricius) (Lepidoptera: Oecophoridae), a potential biological control agent for gorse, *Ulex europaeus* L. (Fabaceae), in Australia

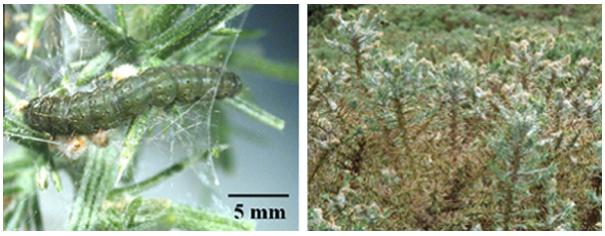
J.E. Ireson [a,*], A.H. Gourlay [b], J.-L. Sagliocco [c], R.J. Holloway [a], W.S. Chatterton [a], R. Corkrey [a]

[a] Tasmanian Institute of Agriculture, University of Tasmania, 13 St John's Avenue, New Town, Tasmania 7008, Australia
[b] Landcare Research New Zealand Ltd., Canterbury Agriculture and Science Centre, P.O. Box 69, Gerald St., Lincoln, New Zealand
[c] 84 Sycamore Road, Frankston South, Vic. 3199, Australia

HIGHLIGHTS

- Tests showed that *Agonopterix umbellana* was safe to release in Australia.
- Establishment confirmed at Tasmanian release sites.
- The life cycle is univoltine with larvae passing through six instars.
- Lower development thresholds and thermal constants for all development stages were determined.

GRAPHICAL ABSTRACT



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ABSTRACT

Host specificity tests on over 250 species or cultivars of plants including 37 Australian native and introduced plant species or cultivars showed that the gorse soft shoot moth, *Agonopterix umbellana*, would be unlikely to survive on any plant other than gorse in Australia. The first field release was at Jericho, Tasmania during spring 2007. By the summer of 2013 high larval densities of *A. umbellana* were evident at the release point, with dispersal recorded to a maximum of 200 m over ca. 2 ha. Recoveries at other release sites in Tasmania as well as in South Australia and Victoria suggest that the species will eventually establish across south-eastern Australia. The life cycle of *A. umbellana* is closely synchronised with gorse phenology. Population increase and dispersal is expected to be slow as a consequence of its univoltine life cycle incorporating the narrow larval feeding period of 3 months when gorse is a suitable food source. At Jericho, oviposition commenced in late winter which enabled hatching to coincide with the presence of new gorse growth for developing larvae. Larvae fed over a 3 month period on new growth available from mid-October to mid-January passing through six instars before pupation. The first adults were recorded in early February emerging in an obligate reproductive diapause which was completed by late July. Controlled temperature cabinets held at 12, 15, 18, 21 and 24 °C were used to estimate lower development thresholds (LDT) and thermal constants. The LDT for eggs larvae, pupae and total development were 8.7, 7.5, 7.9 and 7.9 °C, respectively and the thermal constants were 143.0°, 526.3°, 278.0° and 971.0° degree days respectively. In the long term, it is hoped that *A. umbellana* will contribute to the biological control of gorse in Australia. This will be in combination with the gorse seed weevil, *Exapion ulicis*, the gorse spider mite, *Tetranychus lintearius* and the gorse thrips, *Sericothips staphylinus*, even though earlier studies have shown these other agents are constrained either by predation in the case of *T. lintearius* or the effects of gorse phenology in the case of *S. staphylinus* and *E. ulicis*.

* Corresponding author. Fax: +61 3 6233 6145.
E-mail address: John.Ireson@utas.edu.au (J.E. Ireson).

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1. Introduction

Gorse, *Ulex europaeus* L., is a perennial spiny shrub commonly 1–2.5 m tall that can live for up to 30 years (Lee et al., 1986). A native of Western Europe, gorse was introduced to Australia as a hedge plant in the early 1800s (Parsons and Cuthbertson, 2001) and is now a weed of national significance (Thorp and Lynch, 2000). Gorse occurs in Western Australia, South Australia and New South Wales but the heaviest infestations occur in Victoria and Tasmania. The annual cost of gorse management to agriculture and forestry in Australia has been estimated at $7 million (Anon, 2006). The difficulty and expense of controlling gorse by traditional methods such as herbicides, mechanical clearing and cultivation has resulted in biological control options being investigated. Gorse was originally targeted for biological control in Australia through the introduction of the gorse seed weevil, *Exapion ulicis* (Forster) (Evans, 1942). Additional studies on the biological control of gorse were conducted for a New Zealand program (Hill, 1982, 1983; Hill and O'Donnell, 1991) and this earlier work provided the basis for a new Australian program that was initiated during the late 1990's (Ireson et al., 1999). Since then two additional agents, the gorse spider mite, *Tetranychus lintearius* Dufour and the gorse thrips, *Sericothrips staphylinus* Haliday, have been established in Australia (Ireson et al., 2003, 2008a). The gorse soft shoot moth, *Agonopterix umbellana* (Fabricius 1794) is another potential European biological control agent. It has been established in New Zealand, Hawai'i and Chile but referred to in earlier publications (Hill et al., 1995; Markin et al., 1996; Suckling et al., 2000; Norambuena et al., 2004; Ireson et al., 2004) by its junior synonym, *Agonopterix ulicetella* (Stainton 1849). However, the specific name '*umbellana*' should be used by principle of priority (ICZN, 2007).

This paper presents the outcome of the host specificity tests conducted to obtain approval for the Australian release of *A. umbellana*. Details of the subsequent rearing and release program are also presented together with observations on the biology of *A. umbellana*, the results of establishment surveys and a discussion of the current status of the Australian gorse biological control program.

2. Materials and methods

2.1. Test plants

The Australian host specificity tests involved 37 species or cultivars (including gorse). The list was approved on the basis of tests previously conducted in other countries. These included tests on 138 species or cultivars of plants (Markin and Brown, 1988) enabling the release of *A. umbellana* in Hawai'i in 1988 (Markin et al., 1996) and on over 70 species or cultivars of plants enabling release in New Zealand in 1992 (Hill et al., 1995). Additional supporting data was also used from tests on 11 plant species that enabled release in Chile in 1997 (Martinez et al., 2000).

The choice of species for the Australian tests was based on the strategy detailed by Wapshere (1974) and by using a more recent interpretation of the relationship between the various tribes of the Fabaceae (Sub-family Papilionoidiae (Faboideae)) by Polhill (1981). The selection of species (other than gorse) in the subtribe Genistinae included in the Australian test list (Tables 1 and 2) was based on their use as ornamentals and, in the case of *Chamaecytisus palmensis* (tagasaste), its use as a fodder shrub. Although *C. palmensis* was previously tested by Hill et al. (1995) and Markin and Brown (1988), additional tests were carried out on this species (Table 3) as well as on three commercial cultivars of *Lupinus angustifolius* (Lupininae), due to their importance as fodder crops.

Of the tribes that could be considered close to the Genisteae, the Crotalarieae contain two Australian genera and the Mirbelieae and Bossiaeeae contain many Australian genera. Outside these tribes one Australian species from the tribe Indigofereae, Loteae and Psoraleae was included on the Australian list (Table 1) as they occur within the Australian distribution of *U. europaeus*. The tests carried out by Markin and Brown (1988) and Hill et al. (1995) make up a representative selection across the other groups. These included a number of leguminous plants of economic and environmental importance to Australia. However, because of the importance of plants in the Phaseoleae to Australian agriculture, four species representing four genera of tropical legumes and four cultivars of the temperate legume *Phaseolus vulgaris* were included on the Australian test list. In addition, a native ornamental species in the Phaseoleae, *Hardenbergia violacea*, was also included together with a representative of the Trifoliae, *Trifolium subterraneum*. Outside the Faboideae the genus *Acacia* in the sub-family Mimosoideae is important to Australia and the common Australian species, *Acacia dealbata* and *Acacia mearnsii*, were included in this test list.

2.2. Location of host specificity tests and source of material

Oviposition and larval feeding tests were initially conducted at or near Landcare Research New Zealand at Lincoln and on the Island of Hawai'i between March 2001 and May 2002. On Hawai'i, field experiments were conducted at Humu'ula on the south-eastern side of Mauna Kea volcano at ca. 2200 m where the islands main gorse infestation is located and *A. umbellana* is well established. An additional series of larval feeding tests were also conducted in Australia at the DPI Victoria quarantine facility at Frankston between May and July 2004. The tests in New Zealand were conducted on 34 species and cultivars of Australian plants (including gorse). Some of these plants were grown in the Landcare Research nursery at Lincoln, New Zealand, using seed obtained from Australia and others were imported into the Lincoln Invertebrate Containment Facility (LICF) from Australia as cut shoots. One species, *Pultenaea juniperina*, was imported as both whole plants and cut shoots. In addition to the Australian plants that were used in these tests, gorse from New Zealand was also included. Shoots of gorse from New Zealand were cut at the same time as the Australian test plant shoots were imported, then checked for *A. umbellana* eggs prior to their use as the control material for the tests. All laboratory tests were conducted in the LICF at 15–23 °C, 16:8 h (L:D) and a relative humidity of ca. 70%. Adult *A. umbellana* used in the Lincoln tests were field collected in Hawai'i, over-wintered in the USDA Institute of Pacific Islands Forestry Hawai'i Volcanoes National Park Quarantine Facility then consigned to the LICF where mating and egg laying took place. In May 2002, potted *P. juniperina* plants were air-freighted to Hilo, Hawai'i. Gorse plants of similar age and size were also collected from the field in Hawai'i. Fifteen plants of both species were then potted into planter bags of potting soil, treated with Marathon® (a.i. 1% Imidacloprid) systemic insecticide granules to remove any unwanted invertebrates and used for a subsequent field cage oviposition experiment.

To obtain a further assessment of risk for species of *Pultenaea*, 1560 eggs of *A. umbellana* were imported to Australia from Chile on 14 October 2003. Second generation larvae from this culture were used for the tests conducted in quarantine at Frankston in 2004 on *Pultenaea pedunculata*, *Pultenaea daphnoides* and *P. juniperina*. Additional tests were also carried out on *Glycine max* (soy bean) and *C. palmensis* (tagasaste) to check results in earlier studies. Plants used in the Frankston tests were grown in 15 cm pots. The *Pultenaea* species were obtained from a local nursery, *G. max* plants were propagated from seeds and those of *C. palmensis* were collected from the field. Some tests on *C. palmensis* were also con-