AUSTRALIAN JOURNAL of ENTOMOLOGY

Australian Journal of Entomology (2013) **52**, 246–258

Biological control of western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), in gerberas, chrysanthemums and roses

Andrew G Manners,[1]* Brock R Dembowski[1,2] and Madaline A Healey[3,4]

[1]*Queensland Department of Agriculture, Fisheries and Forestry, Redlands Research Facility, PO Box 327, Cleveland, Qld 4163, Australia.*
[2]*Queensland Department of Agriculture, Fisheries and Forestry, PO Box 1085, Townsville, Qld 4810, Australia.*
[3]*Department of Agriculture, Fisheries and Forestry, Gatton Research Station, Warrego Highway, Gatton, Qld 4343, Australia.*
[4]*Centre for Plant and Water Science, Central Queensland University, Bundaberg, Qld 4770, Australia.*

Abstract *Frankliniella occidentalis* (Pergande), western flower thrips (WFT), is a major worldwide pest of vegetables and ornamental crops. The biology of WFT was examined on gerberas, chrysanthemums and roses in relation to plant stage (flowering and non-flowering), pupation site, soil moisture and plant parts often inhabited by adult and immature thrips. Four foliage thrips predators (*Transeius montdorensis* (Schicha), *Orius armatus* (Gross), *Mallada signata* (Schneider) and *Neoseiulus cucumeris* (Oudemans)) and three soil predators (*Geolaelaps aculeifer* (Canestrini), *Steinernema feltiae* (Filipjev) and *Dalotia coriaria* (Kraatz)) were studied to determine their ability to reduce the numbers of WFT on gerberas, chrysanthemums and roses. There was no difference in the number of adults that emerged from growing media of high or low moisture content on any host plant. There were also no differences in the total numbers of WFT recaptured from flowering gerberas, chrysanthemums or roses. However, about seven times the number of thrips were collected from flowering chrysanthemums compared with non-flowering chrysanthemums, indicating that the flowering plants were more suitable hosts. Of all thrips recollected, the greatest percentage was immature (larval and pupal) thrips (70%, 71% and 43%) on the flowers for gerberas, chrysanthemums and roses, respectively. The mean percentage of thrips that emerged as adults from the soil was very low (5.3 ± 1.2, 8.5 ± 2.9, 20.5 ± 9.1 and 28.2 ± 5.6%) on gerberas, flowering and non-flowering chrysanthemums, and roses, respectively. Simultaneous release of foliage and soil predators did not reduce the number of thrips beyond that caused by foliage predators alone. Of the foliage predators, *T. montdorensis*, *O. armatus* and *N. cucumeris* performed best, significantly reducing the numbers of adult and immature thrips on flowers and foliage by 30–99%. Further research is required to determine the most cost-effective rates of release in cut flower crops.

Key words biocontrol, cut flower production, insect–plant interaction, integrated pest management, *Transeius montdorensis*.

INTRODUCTION

Frankliniella occidentalis (Pergande), western flower thrips (WFT), is a major worldwide pest of vegetables and ornamental crops. Since its discovery in Australia in 1993 (Malipatil *et al*. 1993), WFT has been associated with serious economic losses in a wide range of horticulture crops, including strawberry, cucumber, tomato, capsicum, nursery ornamentals, and cut flowers such as gerbera, chrysanthemum, dahlia, lisianthus and rose crops (Lewis 1997).

Several factors contribute to the high impact of WFT, such as its ability to reproduce on a large number of hosts, its rapid developmental cycle and high reproductive rate, and its tendency to inhabit protected areas of the plant, such as growing tips and flower buds (Childers 1997). In the cut flower industry, economic loss results mainly from scarring and malformation; for some crops, growers indicate that as little as 5–10% damage can deem flowers unmarketable, e.g. chrysanthemums. Infestations of WFT can also slow or stunt growth of foliage and can transmit several plant viruses (e.g. tomato-spotted wilt virus), which can devastate susceptible crops. Costs associated with chemical control of WFT can be high; in California, it has been suggested that 7.5% of total product cost in cut flower industries is spent on WFT control (Murphy *et al*. 1998). Quantitative economic loss to cut flower industries has not been estimated in Australia, but the industry considers it the highest priority pest, although some growers consider two-spotted mite (TSM) to be equally important.

*andrew.manners@uqconnect.edu.au

doi:10.1111/aen.12020

An intensive pesticide regime is often implemented to control WFT, which has led to varying levels of pesticide resistance across a wide range of chemicals (Herron & James 2005, 2007). This often results in growers resorting to 'hard' chemicals that also kill beneficial organisms and can prove ineffective. As a result, WFT remains a problem on the crop, and other pests, such as TSM, may proliferate. This highlights the need for alternative methods of sustainable and reliable WFT control implemented as part of an integrated pest management (IPM) program.

Larvae and adult WFT feed on foliage and flower tissue, with pupation occurring on the plant or in the soil. There are commercially available predators that consume pupae in the soil, immature stages on foliage and adults on foliage. In Australia, some of the biological control agents have been studied internationally, particularly *Neoseiulus cucumeris* (Oudemans), *Orius* spp., *Geolaelaps* (= *Hypoaspis*) *aculeifer* (Canestrini), *Steinernema feltiae* (Filipjev), and to a certain extent *Transeius montdorensis* (Schicha). Other biological control agents, *Orius armatus* (Gross), *Mallada signata* (Schneider), and *Dalotia coriaria* (Kraatz), have not yet been researched to such an extent in Australia or internationally.

Effect of soil moisture on thrips mortality

Soil moisture can positively or negatively affect mortality of soil-inhabiting insects (Grigorov 1974). Similarly, irrigation type and frequency has had a positive, negative or neutral relationship with thrips survival. Two studies examining the effect of soil moisture and irrigation on WFT abundance did not show an appreciable difference across treatments (Schuch *et al*. 1998; Latimer & Oetting 1999), although this may have been confounded by the indirect methods used by Latimer and Oetting (1999).

There is some evidence that individual species may react to soil moisture similarly across host plant species, e.g. *Thrips tabaci* (Lindeman) on cucumbers, garlic and onions (Bieri *et al*. 1989; Kannan & Mohamed 2001; Chhatrola *et al*. 2006). However, there are insufficient data to suggest that any given thrips species will always react to soil moisture in the same way across host plant and soil media. If a certain level of soil moisture can be shown to increase mortality of WFT, it may be possible to modify irrigation to improve control in cut flower crops.

WFT soil biological control agents

In Australia, there are four commercially available WFT soil predators, *S. feltiae*, *G. aculeifer*, *Stratiolaelaps scimitus* (= *Hypoaspis miles*) (Berlese) and *D. coriaria*. Internationally, research has shown significant WFT mortality associated with soil predators. The exact species, culture (for nematodes) and combination of predators applied played a critical role in the level of WFT mortality, which was often 40–80% (Ebssa *et al*. 2001a, 2004; Premachandra *et al*. 2003a; Berndt *et al*. 2004; Belay *et al*. 2005). This indicates that different 'strains' or formulations of each species of nematode have differential virulence to WFT. Combinations of predatory mites and nematodes have reduced populations of WFT more than those treatments where mites or nematodes were applied separately (Premachandra *et al*. 2003b). Combining soil predatory mites and chemical control resulted in 99% WFT mortality on bean plants (Thoeming & Poehling 2006). In the laboratory, *G. aculeifer* has been shown to be more voracious than *S. scimitus* (Borgemeister *et al*. 2002); therefore, only *G. aculeifer* was examined here.

The effectiveness of *S. scimitus*, *G. aculeifer* and *D. coriaria* as biological control agents is somewhat unclear. On some occasions, *S. scimitus* and *G. aculeifer* do not produce noticeable control of WFT, even at high rates of release (Beerling 2008). However, on chrysanthemums, both *S. scimitus* and *G. aculeifer* reduced adult WFT by about 50% (Bennison *et al*. 2002a; Messelink & van Holstein-Saj 2008). *Steinernema feltiae* has also been shown to produce a 74% reduction of adult WFT on chrysanthemums, although unacceptable levels of damage were still observed (Arthurs & Heinz 2006; Beerling 2008). On mini-roses, *D. coriaria* has been found to consume large numbers of thrips larvae and pupae, and anecdotal evidence also indicates thrips reductions in commercial rose farms (Carney *et al*. 2002). These studies have led to speculation over the efficacy of these agents to control WFT under Australian conditions within the cut flower industry. One of the major drawbacks of many of these studies is that they are primarily based on small-scale laboratory experiments, and thus have limited utility for making inferences on a commercial scale.

WFT larval and adult foliage predators

In Australia, there are three commercially available foliage thrips predators, *O. armatus*, *T. montdorensis* and *N. cucumeris*. In addition, there is some question of the ability of the green lacewing, *M. signata*, to contribute to WFT mortality, as it has not yet been tested. In Australia, *O. armatus* and *T. montdorensis* have only recently become commercially available.

Research indicates varied success using *N. cucumeris* as a sole treatment against WFT populations, from sufficient control to unacceptable damage on chrysanthemums (Hessein & Parrella 1990; Beerling 2008), roses (Vanninen & Linnamaki 2002; Pijnakker & Ramakers 2008) and other crops (Williams 2001; Bennison *et al*. 2002b; Boullenger & Turquet 2011). Significant economic loss has resulted despite reductions of WFT numbers of up to 96% in some cases, indicating the low economic threshold of WFT (Beerling 2008). Frequent release of high numbers of *N. cucumeris* (from 100 to 1000 mites per m^2) appears more likely to keep WFT numbers below economic thresholds (Williams 2001; Pizzol *et al*. 2009; Goette & Rybak 2011).

Conversely, *Orius* spp. has been shown to reduce WFT numbers below economic thresholds at much lower rates in gerberas, chrysanthemums and roses (Cook *et al*. 1996; Bueno *et al*. 2003, 2009; Carvalho *et al*. 2008). On carnations, WFT

were significantly reduced by *O. armatus* when predator abundance increased above one adult per flower (Cook *et al*. 1996).

Transeius montdorensis has been used in commercial cucumber, capsicum, tomato, strawberry, gerbera and chrysanthemum crops to manage WFT successfully, with occasional pesticide applications as required (Steiner 2002; Steiner & Goodwin 2002). On strawberries, *T. montdorensis* has been shown to reduce thrips numbers significantly more than *N. cucumeris* (Rahman *et al*. 2011a,b,c, 2012).

The above research indicates that biological control agents have been used to varying degrees of success to manage WFT. Therefore, a more thorough understanding of the potential use of predators is required for Australian cut flower growers. In this study, Australian commercially available predators were tested on gerberas, chrysanthemums and roses to determine their efficacy in reducing populations of WFT. In addition, aspects of WFT general biology were investigated to help clarify differences in survival and pupation behaviour on gerberas, chrysanthemums and roses.

In this paper, experiments were split into two major areas. First, the biology of WFT was investigated, in relation to pupation site and survival, on gerberas, chrysanthemums and roses. For chrysanthemums, the effect of flowering and vegetative plants was studied. In addition, the effect of soil moisture on pupal survival (for those thrips that pupated in the soil) was examined. Second, biological control experiments were conducted to ascertain which commercially available predators, or combination of predators, had the greatest reduction on the numbers of WFT. The following species were tested: *T. montdorensis*, *O. armatus*, *M. signata*, *N. cucumeris*, *G. aculeifer*, *S. feltiae* and *D. coriaria*.

MATERIALS AND METHODS

Experiments were maintained at the Redlands Research Facility, Cleveland, Queensland, Australia. Experimental methods are split into general biology (including the effect of soil moisture) and biological control experiments.

Plants

Gerberas and roses were grown in 100% coconut coir (EC 0.35). Plants were fertilised using Osmocote® Exact® 6-month slow release incorporated into the coir at about 10 kg/m^3. About one tablespoon of Osmocote was reapplied every 3 months on top of the coir. Chrysanthemums were grown in 95% composted pine bark (10 mm), 5% coir peat and fertilised with Osmocote® Exact® 6-month slow release at 5 kg/m^3. *Gerbera jamesonii* (Bolus ex Hook.) cultivars 'Fiorella' and 'Intense' were used for Western flower thrips (WFT) biology and biological control experiments, respectively. The rose cultivar 'Adrenalin' (*Rosa* sp.) and chrysanthemum cultivar 'Aliya' (a red spray *Chrysanthemum* sp.) were used in both WFT biology and biological control experiments. At the time of conducting general biology experiments, Fiorella gerberas were between 6 and 12 months old, and roses were between 18 and 24 months. Gerbera Intense plants were between 3 and 12 months old when used in the biological control experiments. All chrysanthemums were less than 3 months old at the time of experimentation. All plants were irrigated as required, generally three to four timers per day for 5–10 min using two drips per pot depending on the season.

Thrips

Thrips were obtained from a culture maintained by Leigh Pilkington (NSW Department of Primary Industries), and were reared using a method based on DeGraaf and Wood (2009). References to immature thrips refer to larvae and pupae combined.

General biology experiments

Each plant was placed in a cage made of a flexible transparent PVC square top (20 cm wide). Thrips-proof polyester mesh (90 μm holes) was glued to the PVC using PVC-u pipe cement and clear silicone sealant, and hung 80 cm from the top. The bottom of each cage was secured to pots using a strong rubber band. Irrigation was inserted through a small hole in the pot below the rubber band. Cage tops were supported using bamboo stakes. All experiments were conducted in a temperature-controlled glasshouse at 24 ± 5°C, at ambient humidity (mean of about 80% RH, generally ranging between 60% and 90% RH as measured from one Tinytag). The glasshouse was covered with a solar reflectant aluminium shade cloth that transmitted about 30% of ambient light.

For each host plant, two levels of soil moisture were tested. Low soil moisture was the minimum amount of water required to keep plants from becoming water stressed, as indicated by wilting leaves. In the glasshouse environment, this generally amounted to about 200 mL of water every 3–4 days. High soil moisture kept growing media saturated during the entire experiment (two watering events of 400 mL each). In addition, low and high soil moisture treatments had one and two irrigation spikes, respectively. The low treatment spike was placed centrally in the pot, and the two spikes of the high treatment were placed on opposite sides of the plant, half way between the centre and the edge of the pot.

Fifty newly emerged (within 24 h) first instar larvae were placed in each cage in small portion containers. At least one leaf was touching the inside of the container to aid thrips moving onto plants. Dead thrips were not found in portion containers at the end of experiments, indicating that this method successfully transferred thrips. After 8 days, plants were cut at ground level. Foliage and flowers were placed into separate bucket traps with yellow sticky traps placed above and below plant material. Flower buckets were 115 and 105 mm in diameter at top and base, and 120 mm deep. Foliage buckets were 265 and 190 mm at top and base, and 245 mm deep.

Sticky traps were constructed from laminated yellow card (a 30 cm rule was taped to the back of large traps to provide support), covered in plastic wrap and a thin layer of Tangle

Trap® – Insect Trap Coating, applied just prior to use. Circular traps were placed in the bottoms of flower and foliage buckets that fit securely. A paper binder (25 mm) was punctured through the centre of the traps to aid in placement and removal of traps. Square wire meshes (20 mm holes) were folded and placed on top of the bottom traps, raising flowers and foliage about 20–30 mm above traps, preventing plant material from sticking directly to the bottom traps. Flat mesh was placed in between top traps and the bucket lid, preventing top traps from sealing the bucket (otherwise, samples did not dry, encouraging fungal growth). Flower and foliage top traps were 200 × 170 mm and 340 × 340 mm. In addition, a sticky trap was placed 340 × 300 mm above the growing media. Sticky trap placement allowed for collection of adult and immature stages (larvae and pupae) from foliage and flowers, and adults from the soil. The number of adult and immature thrips collected from soil, foliage and flowers was recorded after 2 weeks. Adult thrips were collected and identified under a stereo microscope (using pronotum and ocular setation to confirm the identity of WFT). In general, WFT and *T. tabaci* were easily identified, while a small minority of individuals of other species remained unknown.

Chrysanthemum trials were done in August and repeated in September 2010. Each trial comprised 40 plants divided equally between five replicates in a randomised complete block design, i.e. eight plants per replicate. Each replicate contained the following treatments: moisture high (H), moisture low (L), flowering plant (F), non-flowering plant (N), thrips added (T) and control (C – i.e. no thrips). Thus, a chrysanthemum replicate (complete block) was comprised in random order: HFC, HFT, HNC, HNT, LFC, LFT, LNC and LNT. Flowering plants had some fully opened flowers, some at the bud burst stage and some unopened buds. No buds were present on non-flowering plants.

Since roses and gerberas flower continuously, and plants produced flowers within the time frame of experiments, flowering and non-flowering plants were not tested. Instead, flowering roses and gerberas were tested simultaneously. Combined rose and gerbera trials were done in August, November (early) and November (late) 2010. Each trial comprised the same plant/replicate/RCB design as above for chrysanthemums. Each replicate contained the treatments: rose (R), gerbera (G), moisture high (H), moisture low (L), thrips added (T) and control (C, i.e. no thrips added). Thus, a randomised complete block of eight plants included in random order GHFC, GHFT, GLFC, GLFT, RHFC, RHFT, RLFC and RLFT.

Therefore, all trials had eight plants in each randomised complete block. Over all trials, there was a total of 10 replicates completed for chrysanthemums, and 15 for gerberas and roses.

Biological control experiments

A total of eight trials were conducted to test how well foliage and soil dwelling predators were able to reduce the numbers of WFT on gerberas, chrysanthemums and roses. It was intended to complete one trial testing foliage predators (*M. signata*, *N. cucumeris*, *O. armatus* and *T. montdorensis*) and one trial testing soil predators (*D. coriaria*, *G. aculeifer* and *S. feltiae*) for each host plant. Based on these results, a combination of the most promising foliage and soil predators would be tested simultaneously in the same cage. This was only possible for gerberas and chrysanthemums; only two trials were conducted for roses (Table 1).

Each trial comprised 20 cages divided equally among four or five replicates, depending upon the number of treatments conducted in the trial, split equally among the cages (Table 1). Cages were 600 × 650 × 800 mm WxDxH with 90 µm polyester mesh to prevent thrips and predators from escaping; the cage frame was sealed using clear silicone sealant to eliminate gaps. Plants were irrigated using two drippers, and watered for 3 min, three times per day. Plant pots were placed into 5 L plastic containers with a hole in the lid that allowed the pots to fit in the container securely. This prevented water from inundating cages and potentially causing thrips mortality. Glasshouse temperature was set to 20°C between 19:00 h and 7:00 h, 22°C between 19:00 h and 9:00 h, 25°C between 9:00 h and 16:00 h, and 22°C between 4:00 h and 19:00 h. Solar reflectant aluminium shade cloth that transmitted about 30% of ambient light covered the glasshouse during the experiments.

Biological control agents were added twice, first on the same day as thrips, and second 1 week after the trial commenced. Predators were released on each plant at the following rates for treatments in which the predator was tested: three *D. coriaria* (two adults, one larva), 25 *G. aculeifer*, three larval *M. signata*, 25 *N. cucumeris*, three *O. armatus* (generally two adults and one nymph but sometimes insufficient nymphs were available, thus three adults were released instead), 250 000 *S. feltiae* in 100 mL of water and 25 *T. montdorensis*. There were four plants of the same species in each cage, thus four times the above number of predators were released in each cage in which the predator was being tested. Tests to determine the most effective foliage and soil predator (trials 1–3 and 5–6) had 25 thrips added to each plant (100 per cage) at the beginning of each trial, which included five young adults (emerged within 3 days), 10 L1s and 10 L2s per plant. This was designed to maximise the likelihood of observing a predator producing a significant effect. For trials testing combinations of the most effective foliage and soil predators (trials 4, 7 and 8), only five newly emerged adult WFT were added to each plant. This was designed to reflect a more realistic scenario in which WFT might be blown into a crop during spring.

Gerberas and roses produce flowers on a continuous basis, and were therefore harvested periodically. During trials 1, 5 and 6 (Table 1), a subset of flowers were removed every 5–7 days (only relatively old flowers were cut, i.e. well after flowers would have been harvested in a commercial setting). Removed flowers were beaten to dislodge thrips and placed in bucket traps as per flowers from biology experiments described above; dislodged thrips were returned to the cage. Adult thrips collected from traps were identified under a

Table 1 Summary of the treatments, replication and host plants used in each biological control trial

Trial #	Host plant	Date commenced	Treatments	Reps	Max temp	Mean temp 1000–1500	Mean min humidity	Mean max humidity	Mean humidity
1	Gerbera	30 March 2011	C, Ms, Nc, Tm	5	37.3 ± 0.6	33.8 ± 0.5	59.7 ± 1.6	99.4 ± 0.3	86.2 ± 0.6
2	Chrys.	10 May 2011	C, Ms, Oa, Tm	5	33.2 ± 0.4	30.7 ± 0.3	44.0 ± 1.1	76.7 ± 1.5	64.2 ± 1.4
3	Chrys.	10 June 2011	C, Ga, Sf, Dc	5	32.6 ± 0.4	30.3 ± 0.3	37.9 ± 1.1	66.3 ± 1.2	53.5 ± 1.2
4	Chrys.	7 September 2011	C, Tm, TmSf, OaGa, TmGa	4	35.4 ± 0.3	32.8 ± 0.4	34.7 ± 0.9	74.3 ± 1.3	56.4 ± 1.1
5	Gerbera	14 October 2011	C, Ga, Sf, Dc	5	36.3 ± 0.5	33.5 ± 0.5	50.3 ± 1.8	92.8 ± 0.8	75.3 ± 1.1
6	Rose	23 November 2011	C, Oa, Tm, Sf, Ga	4	35.3 ± 0.5	32.2 ± 0.5	56.3 ± 1.3	93.9 ± 0.7	80.2 ± 0.8
7	Gerbera	10 January 2012	C, Oa, OaSf, Tm, TmOaSf	4	34.5 ± 0.6	31.5 ± 0.6	60.4 ± 2.2	95.6 ± 0.6	83.4 ± 1.1
8	Rose	7 February 2012	C, Oa, OaGa, Tm, TmGa,	4	37.4 ± 0.4	34.0 ± 0.3	Malfunction in both humidity loggers prevented acquisition		

In addition, mean temperature and humidity are presented (mean ± 1 SE). Controls (C) had thrips added but no predators; predator treatments included *Dalotia coriaria* (Da), *Geolaelaps aculeifer* (Ga), *Mallada signata* (Ms), *Neoseiulus cucumeris* (Nc), *Orius armatus* (Oa), *Steinernema feltiae* (Sf) and *Transeius montdorensis* (Tm). Treatments in which more than one predator were released in a cage are presented next to each other (e.g. TmSf had both Tm and Sf released in each cage).

stereo microscope. Four weeks after commencement of the experiment, all flowers were harvested and placed in flower bucket traps. All foliage was beaten to dislodge thrips, which were then collected and identified. Sticky traps were placed over growing media of two randomly selected plants to trap adults emerging from soil. Thrips were collected from soil and flower bucket traps 2 weeks after being set up and identified as per above.

Thrips numbers were observed to decrease throughout the course of trials 1, 5 and 6, with flower harvesting recognised as a potential cause. Therefore, in trials 7 and 8, using combinations of predators on gerberas and roses, flowers were not harvested until the end of the trial. Trials were run for 3 weeks, similar to chrysanthemum trials. Predators were released in weeks one and two. Flowers and foliage were beaten once per week, the number of adult and immature thrips counted, and returned to the cage.

Since chrysanthemums do not produce flowers continuously, trials 2–4 were timed so that flowering occurred during the experiment. Flowers and foliage were beaten once per week, the number of adult and immature thrips counted, and returned to the cage; all flowers were harvested at the end of the trial. Experimental protocol followed as above, with plants beaten once per week, the number of adult and immature thrips counted, and returned to the cage. The number of adult and immature thrips per flower was calculated from a subset of 15 flowers per plant. Chrysanthemum experiments were run over 3–5 weeks dependent upon timing of flowering.

The number of thrips on plants prior to the experiments was monitored by beating all plants. Any adult found was identified under a stereo microscope as per the methods previously described. On average, less than one thrips was collected per cage prior to experimental set-up.

Temperatures and humidity loggers were placed in two cages. Temperature was measured using Thermocron mini temperature loggers (model TCS1). Humidity and temperature were logged using a Hygrochron temperature and humidity button (HC1). Temperature buttons were placed near the base of pots on the side of the cages, while humidity/temperature buttons were placed near the tops of the same cages. All loggers recorded temperature and or humidity (±0.5°C and ±5% RH) every 15 min.

Statistics

Statistical tests were carried out in R 2.11.1 (R Development Core Team 2010). Mixed effects models were used wherever possible. However, the numbers of thrips in some treatments were so low as to preclude formal statistical analysis. The numbers of thrips were often square root transformed, but log+1 or sine transformations were sometimes used depending on the data, and in some instances transformations were not required. Generalised linear hypotheses tests, based on Tukey's test, were used to distinguish between treatments for all mixed model analyses.

General biology experiments

To determine the effect of irrigation on thrips abundance, linear mixed effects models were calculated on the total number of adult and immature thrips per plant (response variables), with irrigation and host plant (gerberas and roses only – chrysanthemums could not be compared directly because they were tested in different experiments) as fixed effects, and trial as a random effect. For chrysanthemums, linear mixed effects models were calculated on the total number of adult and immature thrips per plant, with irrigation and stage (flowering and non-flowering) as fixed effects and trial as a random effect. Variances were weighted by host plant (for gerberas and roses) and stage (for chrysanthemums) to accommodate heteroscedasticity. For all models, the log-likelihood was maximised. Since irrigation was not found to have a significant effect, data were pooled for each host plant for further analyses. The total number of adult and immature thrips (tested separately) per plant was compared across chrysanthemum stage using mixed model analyses, with trial as a random factor. Variances were weighted by stage to accommodate heteroscedasticity.

Non-parametric tests were used to determine if there were differences in the number and stage (adults and immatures) of thrips across plant parts (flowers, foliage soil) for gerberas, roses and chrysanthemums (each host plant tested separately). Parametric tests were not possible due to extremely non-normal data and unequal variances. Separate Kruskal–Wallis tests were completed for gerberas, roses, flowering chrysanthemums and non-flowering chrysanthemums. Plants that did not have thrips added to them (i.e. control plants) were excluded from the analyses, as it was not relevant to examine differences in thrips abundance across plant structures on plants on which thrips were not released.

There were two approaches for calculating the proportion of thrips that pupated in the soil: (1) to assume that only adults emerged from the soil pupated there, or (2) in addition to adults that emerged from soil, to assume that immatures recaptured on traps underneath flowers and foliage were attempting to pupate in the soil; the alternative to option two being that immatures captured under foliage and flowers were simply moving out of plant material because it was no longer a suitable food source or habitat, but would otherwise have pupated either on the foliage or in flowers. The proportion of adults emerging from the soil and immatures trapped under foliage and flowers was calculated separately for gerberas, roses, flowering and non-flowering chrysanthemums, excluding control plants.

Biological control experiments

The number of adults and immatures per flower, adults and immatures per plant, and adults emerging per pot were tested separately across predator treatments for all trials. Where substantial numbers of *T. tabaci* were recorded, analyses were run separately on WFT and *T. tabaci*. As thrips species did not alter patterns in results, only the total numbers are presented, with WFT % presented where necessary.

Where possible, linear mixed effects models were calculated. Biological control agent species was the only fixed effect in all trials. Variances were weighted by biological control agent species to accommodate heteroscedasticity, where needed; variances across treatments were often equal. Individual cages or entire replicates were calculated as mixed effects, depending upon the behaviour of variances across treatments. In trials 7 and 8, where combinations of predators were released on gerberas and roses, statistical analyses were not performed. Results for adult and immature numbers collected from foliage and the number of adults that emerged from soil were highly variable and zero-inflated. The total number of thrips collected per cage (summed across all four plants per cage) was tested using the same statistical analysis.

RESULTS

General biology

The level of soil moisture did not affect the number of adult or immature WFT recovered on gerberas, chrysanthemums or roses (Tables 2,3; Fig. 1). The total number of adult and immature thrips collected from roses was lower than that on gerberas, but was not statistically significant (Tables 2,3; Fig. 1). The number of WFT collected from control plants was significantly lower than those that had thrips added for all host plants (Tables 2,3); for gerberas, chrysanthemums and roses, the number of thrips collected from control plants was about 6%,

Table 2 Statistics from analyses examining the effect of host plant (gerbera or rose) and level of soil moisture (high or low) on the number of adults and immatures per plant

Source	Adults			Immatures		
	Slope estimate	Standard error	*P*	Slope estimate	Standard error	*P*
Intercept	0.310	0.303	0.309	0.356	0.582	0.543
Treatment	1.701	0.397	<0.001	0.440	0.708	<0.001
Irrigation	0.187	0.397	0.640	0.133	0.708	0.851
Host plant	0.023	0.336	0.945	0.218	0.650	0.738
Treatment × irrigation	0.356	0.568	0.528	0.217	1.002	0.829
Treatment × host plant	–0.107	0.475	0.822	–1.558	0.919	0.093
Irrigation × host plant	–0.159	0.475	0.738	–0.299	0.919	0.745
Treatment × irrigation × host plant	–0.140	0.671	0.836	–0.667	1.300	0.609

DF = 110. See methods for model details.

Table 3 Statistics from analyses examining the effect of stage (flower or non-flowering) and level of soil moisture (high or low) on the number of adults and immatures per plant present on chrysanthemums only

Source	Adults			Immatures		
	Slope estimate	Standard error	*P*	Slope estimate	Standard error	*P*
Intercept	0.000	0.254	1.000	0.000	0.561	1.000
Treatment	1.700	0.340	<0.001	2.608	0.736	<0.001
Irrigation	0.100	0.340	0.769	0.000	0.736	1.000
Phenotype	0.100	0.322	0.757	0.000	0.581	1.000
Treatment × irrigation	0.051	0.481	0.915	0.605	1.041	0.563
Treatment × stage	−1.062	0.455	0.022	−2.113	0.822	0.012
Irrigation × stage	0.100	0.455	0.827	0.100	0.822	0.904
Treatment × irrigation × host plant	−0.051	0.654	0.937	−1.071	1.163	0.360

DF = 71. See methods for model details.

and 1% and 9% of that on treatments where thrips had been added. Plant stage strongly affected the number of adult and immature WFT recovered on chrysanthemums; flowering plants had about seven times as many thrips as non-flowering chrysanthemums (Tables 3,4, Fig. 1).

The area of the plant significantly affected the number of WFT collected on gerberas ($\chi^2 = 44.224$, d.f. = 4, $P < 0.0001$) and flowering chrysanthemums ($\chi^2 = 18.991$, d.f. = 4, $P = 0.0007$), but not for non-flowering chrysanthemums ($\chi^2 = 4.064$, d.f. = 2, $P = 0.1311$) or roses ($\chi^2 = 6.463$, d.f. = 4, $P = 0.1672$) (Table 4, Fig. 1). The majority of thrips collected from all host plants were immatures on flowers (70%, 71% and 43% on gerberas, flowering chrysanthemums and roses, respectively). For gerberas, the number of adults and immatures on flowers was equal to each other, but significantly greater than other stages and areas of the plant (Table 4).

The rate of pupation in the soil varied considerably depending on the host plant and method by which it was calculated. The percentage that pupated in the soil, calculated only from adults that emerged from soil, was extremely low (5–30%). Inclusion of immatures trapped below foliage and flowers shifted the mean proportion of thrips that pupated in the soil to 40–67% (Table 5).

Biological control experiments

The number of adults and immatures per flower, adults and immatures per plant on foliage, and the total number of adults emerging from soil were significantly affected by biological control agent species on gerberas, chrysanthemums and roses (Tables 6–9). Statistically significant reductions in thrips ranged between 30% and 99% and varied by biological control agent species, host plant, the stage of thrips and plant location. While results were quite variable, a number of trends can be summarised.

All but one biological control agent (*D. coriaria*) produced one or more significant reductions in the numbers of immature or adult thrips. Foliage predators rarely reduced the numbers of thrips that emerged from the soil, and soil predators rarely reduced the number of thrips found on flowers or foliage (see Table 8 for an exception). Overall, foliage predators were better able to reduce the numbers of adult and immature thrips on gerberas, chrysanthemums and roses. Predatory mite *T. montdorensis* performed the best, reducing the numbers of adults and immatures on foliage and sometimes on flowers (Tables 6–9; trials 1, 4, 6 and 8). On gerberas, *N. cucumeris* and *T. montdorensis* performed equally (Table 6). Further tests were not completed to compare their efficacy on other host plants. *Orius armatus* performed the next best on chrysanthemums, reducing the number of adult and immature thrips per flower and foliage (Tables 6–9). On chrysanthemums, there was no difference in the numbers of thrips recorded between *T. montdorensis* alone and in combination with either *G. aculeifer* or *S. feltiae* (Table 6). Similar comparisons on gerberas and roses were difficult owing to large errors on control treatments (Tables 6,9). Despite no significant difference, the total numbers of thrips per cage (adults and immatures) for *T. montdorensis* were similar to treatments with both *O. armatus* and *S. feltiae*, and *T. montdorensis*, *O. armatus* and *S. feltiae* combined, with numbers at half that of the controls (Table 6).

Trials with combinations of predators on gerberas and roses (Tables 6,9, respectively) were associated with very low thrips numbers on all treatments, compared with those on chrysanthemums (Table 8). As a result, trials 7 and 8, on gerberas and roses, were not considered to have produced a result from which management decisions could be suggested. Causal factors for these results are not known; abiotic factors (temperature and humidity) appeared within that of other trials that had much higher thrips abundances (Table 1).

DISCUSSION

Western flower thrips biology experiments

The rate of recollection of WFT on gerberas, chrysanthemums and roses was relatively low, being no greater than about 60% on gerberas and lower on other host plants (Table 4). Similar published works have recorded recollection rates of about 50–90% (Broadbent *et al.* 2003; Berndt *et al.* 2004; Buitenhuis & Shipp 2008). Low recapture rates appear to be correlated to the size of the experimental area used, with larger

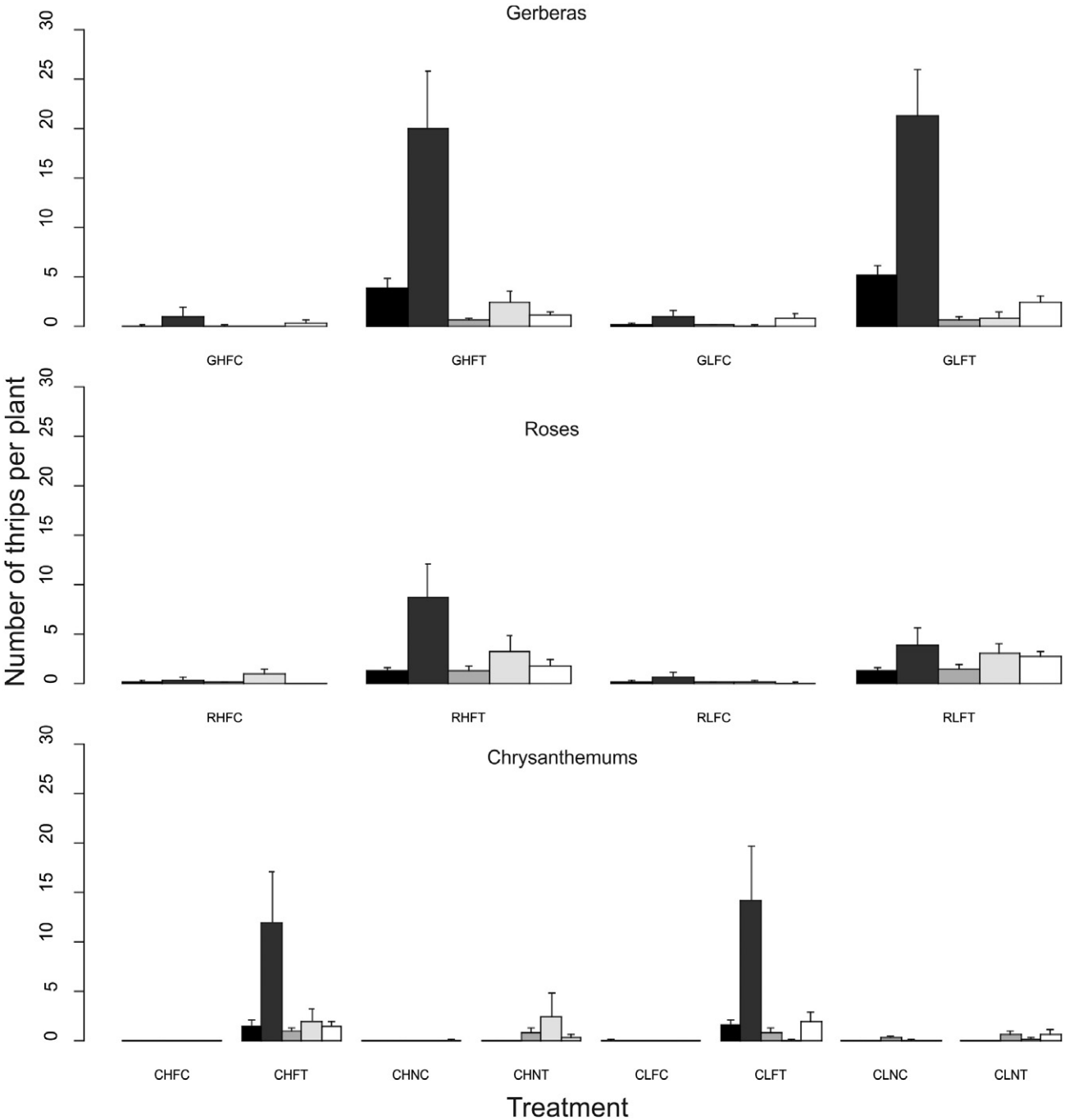

Fig. 1. Adult and immature thrips collected per plant on different areas of gerberas, chrysanthemums and roses (mean ± 1 SE). Treatment abbreviations are as follows: first letter indicates host plant (G = gerberas, R = roses, C = chrysanthemums); second letter indicates level of soil moisture (H = high, L = low); third letter indicates stage (F = flowering, N = not flowering); and fourth letter indicates whether thrips were added (T = thrips added, C = control – no thrips). Where no bar is present, thrips were not collected for that treatment and area of plant. (■) Flower – adults, (■) Flower – immatures, (■) Foliage – adults, (□) Foliage – immatures, (□) Soil – adult.

plants/arenas having lower recapture rates. Plants used in these experiments were often larger than those reported elsewhere and possibly influenced the number of thrips lost. In addition, thrips released onto plants were newly emerged first-instar larvae, not second-instar larvae commonly used in WFT research. These factors may have influenced the recapture rate.

The number of adult and immature thrips collected on roses and gerberas was not significantly different, indicating that they are hosts of similar quality for WFT. Although chrysanthemums were not tested at the same time (and are therefore not directly comparable with data from gerberas and roses), the number of adult and immature thrips collected was similar to that recorded on gerberas and roses. As such, host plant species did not appear to have a significant influence on the numbers of thrips collected across gerberas, flowering chrysanthemums and roses. However, non-flowering chrysanthe-

Table 4 Percentages of adult and immature thrips that emerged from each area on gerberas, flowering and non-flowering chrysanthemums and roses

Pupation sites included	Total % thrips emerging from area per host plant			
	Gerbera	Flowering	Not flowering	Roses
		Chrysanthemums		
Adults on flowers	15.4 a	8.7 b	NA	8.8 a
Immatures on flowers	70.6 a	71.2 a	NA	43.4 a
Adults on foliage	2.4 b	5.2 c	30.1 a	9.9 a
Immatures on foliage	5.6 b	5.7 bc	49.2 a	22.0 a
Adults emerging from soil	6.0 b	9.2 bc	20.7 a	15.9 a
Total number of thrips (total % of thrips recaptured)	879 (58.6%)	368 (36.8%)	53 (5.3%)	434 (28.9%)

Different letters in each column represent statistically significant differences as indicated by separate Kruskal–Wallis tests (see text for significance levels). Since values presented are percentages of all thrips from a given host plant, standard errors are not possible. There were 1500 thrips released on gerberas and roses across 30 replicates, and 1000 thrips released on chrysanthemums across 20 replicates.

Table 5 The mean proportion of thrips per plant (mean ± 1 SE) that pupated in the soil calculated from two different methods, (1) adults emerging from soil only, and (2) adults emerging from soil and immatures that were collected under foliage and flowers, when present

Pupation sites included	Mean percentage of thrips per plant			
	Gerbera	Flowering	Not flowering	Roses
		Chrysanthemums		
Soil adults only	5.3 ± 1.2	8.5 ± 2.9	20.5 ± 9.1	28.2 ± 5.6
Soil adults and immatures trapped below foliage and flowers (when present)	64.9 ± 6.3	42.3 ± 10.2	46.2 ± 9.9	66.9 ± 5.7

Table 6 The effect of biological control agents on WFT numbers (mean ± 1 SE) at the end of trials 1, 5 and 7 on gerberas

Gerbera	Adults per flower	Immatures per flower	Adults per plant on foliage	Immatures per plant on foliage	Adults emerged from soil	Total thrips per cage
Trial 1						NA
Control	4.0 ± 1.3 a	4.8 ± 1.7 a	0.9 ± 0.3 a	2.0 ± 1.2 a	1.6 ± 0.6 a	
Nc	1.4 ± 0.7 a	2.0 ± 0.4 a	0.4 ± 0.2 a	0.2 ± 0.2 b	1.0 ± 0.4 a	
Ms	4.4 ± 1.4 a	3.2 ± 1.9 a	1.3 ± 0.7 a	3.0 ± 1.9 a	4.6 ± 2.7 a	
Tm	2.1 ± 0.5 a	1.6 ± 0.4 a	0.4 ± 0.3 a	0.2 ± 0.1 b	0.5 ± 0.4 a	
Trial 5						NA
Control	1.8 ± 0.9 a	9.3 ± 4.7 a	0.4 ± 0.3 a	1.4 ± 0.6 a	2.0 ± 0.6 a	
Dc	1.0 ± 0.3 a	3.8 ± 0.9 a	0.1 ± 0.1 a	1.6 ± 0.7 a	1.0 ± 0.6 a	
Ga	3.6 ± 2.6 a	18.4 ± 10.7 a	0.4 ± 0.2 a	0.4 ± 0.2 a	1.8 ± 0.8 a	
Sf	0.9 ± 0.2 a	4.9 ± 1.4 a	0.3 ± 0.1 a	0.6 ± 0.2 a	0.6 ± 0.4 b	
Trial 7						
Control	1.0 ± 0.6 a	1.1 ± 0.8 ab	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	14.8 ± 7.2 ab
Oa	2.0 ± 0.7 a	0.3 ± 0.1 a	0.1 ± 0.1	0.3 ± 0.2	0.1 ± 0.1	16.3 ± 4.8 a
OaSf	1.1 ± 0.8 a	0.1 ± 0.1 a	0.3 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	6.8 ± 3.8 ab
Tm	0.6 ± 0.3 a	0.02 ± 0.02 b	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	6.0 ± 2.5 ab
TmOaSf	0.3 ± 0.2 a	0.4 ± 0.2 ab	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	4.0 ± 2.0 b

Different letters in each column within each trial indicate statistically significant differences.
WFT, western flower thrips.

mums were a very poor host compared with the flowering host plants tested here, indicating that the presence of flowers significantly benefited WFT survival. To our knowledge, similar research comparing flowering and non-flowering plants from first instar to pupation has not yet been published; other research generally examines second-instar larvae to pupation or examines the addition of adults and subsequent generations, or was conducted on very small plants (e.g. Ebssa *et al*. 2001b; Broadbent *et al*. 2003; Berndt *et al*. 2004; Wiethoff *et al*. 2004; Buitenhuis & Shipp 2008). Preventative releases of biological control agents when buds first occur on chrysanthemums and other annual flowering cultivars may aid in the control of WFT.

For gerberas and flowering chrysanthemums, flowers housed significantly more thrips than foliage or soil. In biological control experiments, as many as 10–50 immatures were found to drop from the flowers of control gerberas and chrysanthemums. Populations of thrips can easily build to large

Table 7 The effect of foliage biological control agents on WFT numbers (mean ± 1 SE) at the end of trials 2 and 3 on chrysanthemums

Chrysanthemums	Adults per flower	Immatures per flower	Adults per plant on foliage	Immatures per plant on foliage	Adults emerged from soil
Trial 2					
Control	8.5 ± 2.1 a	48.2 ± 3.1 a	13.9 ± 5.3 a	19.5 ± 9.3 a	97.1 ± 9.5 a
Oa	4.9 ± 0.9 a	32.1 ± 6.2 b	4.4 ± 1.5 c	6.8 ± 1.4 a	80.4 ± 20.4 a
Ms	4.9 ± 0.8 a	30.2 ± 4.6 b	6.9 ± 1.3 ab	6.1 ± 1.5 a	65.7 ± 11.2 a
Tm	5.7 ± 1.2 a	30.8 ± 5.0 b	9.2 ± 4.8 bc	4.1 ± 2.4 b	84.0 ± 21.9 a
Trial 3					
Control	6.9 ± 0.9 a	46.5 ± 3.5 a	20.7 ± 3.7 a	14.3 ± 2.3 a	175.2 ± 32.6 a
Dc	7.0 ± 1.0 a	45.0 ± 5.7 a	17.1 ± 1.9 a	26.6 ± 10.9 a	161.9 ± 25.2 ab
Ga	5.7 ± 1.0 a	39.2 ± 3.7 a	12.6 ± 2.1 b	22.4 ± 15.7 a	87.0 ± 7.4 c
Sf	5.0 ± 0.5 a	46.9 ± 2.1 a	33.4 ± 17.5 a	42.1 ± 23.9 a	101.0 ± 15.0 bc

Different letters in each column within each trial indicate statistically significant differences.

Table 8 The effect of foliage and soil biological control agents on WFT numbers (mean ± 1 SE) at the end of trial 4 on chrysanthemums

Chrysanthemums	Adults per flower	% WFT in flowers per cage†	Immatures per flower	Adults per plant on foliage	% WFT from foliage per cage‡	Immatures per plant on foliage	Adults emerged from soil
Control	5.5 ± 2.0 a	49.8 ± 13.3	51.7 ± 14.2 a	9.8 ± 3.2 a	31.1 ± 12.4	47.0 ± 11.7 a	35.0 ± 14.1 a
OaGa	0.5 ± 0.1 b	25.9 ± 9.0	10.3 ± 4.5 b	5.0 ± 3.0 ab	0.0 ± 0.0	3.5 ± 2.3 b	6.3 ± 2.7 b
Tm	0.8 ± 0.1 ab	50.6 ± 5.9	13.2 ± 2.8 b	4.0 ± 0.7 ab	17.5 ± 11.8	0.5 ± 0.3 b	4.8 ± 1.8 b
TmGa	0.6 ± 0.1 ab	43.5 ± 11.8	10.6 ± 3.1 b	1.1 ± 1.1 ab	0.0 ± 0.0	1.3 ± 0.5 b	3.5 ± 1.6 b
TmSf	0.6 ± 0.2 ab	40.6 ± 10.5	10.8 ± 5.4 b	0.9 ± 0.9 b	16.7 ± 16.7	1.3 ± 0.8 b	5.3 ± 1.8 b

Different letters in each column indicate statistically significant differences.
†Only *Thrips tabaci* and WFT were found on flowers. ‡Of 96 adult thrips found on foliage across all cages, only three were not WFT or *T. tabaci*.

Table 9 The effect of foliage and soil biological control agents (tested separately) and combinations of biological control agents on WFT numbers (mean ± 1 SE) at the end of trials 6 and 8 on roses

Roses	Adults per flower	Immatures per flower	Adults per plant on foliage	% WFT from foliage per cage	Immatures per plant on foliage	Adults emerged from soil	Total thrips per cage
Trial 6							NA
Control	1.4 ± 0.2 a	8.4 ± 3.1 a	4.5 ± 1.1 ab	25.0 ± 3.9	12.4 ± 6.1 a	0.4 ± 0.2	
Ga	2.7 ± 1.6 a	6.0 ± 3.5 ab	2.0 ± 1.5 ab	50.0 ± 28.9†	2.6 ± 1.3 a	0.3 ± 0.3	
Oa	1.3 ± 0.2 a	4.5 ± 1.7 ab	4.0 ± 0.7 a	15.4 ± 5.4	4.4 ± 1.8 a	0.6 ± 0.6	
Sf	3.0 ± 1.5 a	11.0 ± 2.9 a	3.5 ± 1.1 ab	18.0 ± 9.1	6.3 ± 2.0 a	1.1 ± 0.8	
Tm	1.0 ± 0.5 a	1.4 ± 0.9 b	1.8 ± 0.3 b	0.0 ± 0.0	2.0 ± 1.0 a	0.1 ± 0.1	
Trial 8				NA			
Control	1.1 ± 0.4 ab	0.2 ± 0.1 ab	0.3 ± 0.1		1.1 ± 0.4	0.1 ± 0.1	21.8 ± 5.8 a
Oa	0.4 ± 0.3 a	0.1 ± 0.06 a	0.3 ± 0.1		0.8 ± 0.5	0.1 ± 0.1	17.8 ± 8.9 a
OaGa	2.4 ± 0.3 b	0.1 ± 0.04 b	0.1 ± 0.1		0.3 ± 0.1	0.1 ± 0.1	37.8 ± 17.6 a
Tm	1.4 ± 0.9 a	0.2 ± 0.1 a	0.4 ± 0.1		0.9 ± 0.4	0.4 ± 0.2	32.8 ± 22.4 a
TmGa	0.8 ± 0.4 a	0.1 ± 0.03 a	0.0 ± 0.0		0.4 ± 0.2	0.1 ± 0.1	16.0 ± 6.3 a

Different letters in each column for each trial indicate statistically significant differences. Where no letters are present in a column, statistical tests were not conducted.
†$n = 3$, no thrips were collected from flowers in one cage.
WFT, western flower thrips.

numbers in a crop simply by allowing thrips to complete development. This highlights and supports the practice of removing old flowers to better manage WFT (Casey *et al*. 2007), despite the possible benefits that pollen provides to predators, such as *O. armatus*, and predatory mites.

On roses, WFT were more randomly distributed across the plant. The largest number of thrips collected was also from flowers; however, there were no significant differences in the number of thrips collected from any area. Likewise, in biological control tests on roses, about 55% of thrips were immatures under flowers on control treatments, and about 33% were immatures from foliage. This contrasts results in roses that showed that the majority of WFT were found near flower buds (Casey *et al*. 2007). However, removal of old rose flowers will still contribute to the management of thrips populations, and may be modified by rose cultivar.

The percentage of adult thrips emerging from the soil was low for all host plants, at 5% on gerberas to 28% on roses. Literature on pupation and distribution of WFT on gerberas, chrysanthemums and roses is variable, with most suggesting very high levels of WFT pupate in the soil. Studies have found 97% pupation on chrysanthemums (stage unknown), about 90% soil pupation on non-flowering chrysanthemums and flowering and non-flowering roses (Bennison *et al*. 2002a), and only 50–60% soil pupation on flowering chrysanthemums (Broadbent *et al*. 2003; Buitenhuis & Shipp 2008). Only rarely have soil pupation rates been recorded at very low rates, e.g. as low as 10% on cucumbers and lettuce (Steiner *et al*. 2011).

If thrips collected from traps under foliage and flowers were considered to be attempting to pupate in the soil, results from this study would be similar to those published in other literature (e.g. Broadbent *et al*. 2003; Buitenhuis & Shipp 2008). WFT are very susceptible to low relative humidity (RH), requiring about 80% humidity to successfully pupate (Steiner *et al*. 2011). Furthermore, Steiner *et al*. (2011) found that about 80% of late-stage, second-instar larvae will drop from foliage when RH drops below 80%. In this study, it seems likely that larvae were simply responding to low RH associated with plant material drying out in traps and not trying to pupate in the soil. As a result, only adults that emerged from soil were considered as the proportion that pupated in the soil. RH was not recordable during WFT biology trials; however, observations found that condensation was present on the PVC tops of all of the cages, indicating that RH was relatively high. Humidity was recorded within cages of biological control experiments (Table 1), and at times recordings were below 80%. During these experiments (trials 3–6), soil pupation was also extremely low (2–6% of thrips collected from control cages at the end of trials 3–6 were adults emerging from soil), and presence in flowers was relatively high. This supports the suggestion that WFT presence in flowers may help buffer against relatively low humidity (Steiner *et al*. 2011), and thus reduce the proportion of thrips that pupate in the soil.

Assuming that low rates of soil pupation are widespread in cut flower crops, management of WFT using soil predators is unlikely to provide substantial levels of control in a cost-effective manner. WFT have been shown to drop directly down from plants, rather than walking down plants or jumping away from plants (Steiner *et al*. 2011). Flower crops often have a low proportion of soil below leaves and flowers, such as roses grown in coir bags, and gerberas often have a large proportion of foliage not directly above growing media. These factors provide further support that managing thrips in growing media of cut flower crops may not significantly contribute to the reduction of WFT populations. A possible exception could be flower crops grown in-ground or hosts that are shown to exhibit high rates of soil pupation.

Western flower thrips biological control experiments

The ability of each biological control agent species to reduce WFT was largely consistent across host plant species, with certain predators producing greater reductions than others. In general, the predatory mite *T. montdorensis* performed best, reducing the number of adult and immature thrips in flowers, foliage and sometimes adults emerging from the soil. Comparisons between *T. montdorensis* and *N. cucumeris* found that both predatory mites reduced the numbers of thrips equally. On strawberries, *T. montdorensis* and *N. cucumeris* were also able to reduce thrips numbers similarly, although *T. montdorensis* was able to reduce WFT slightly more than *N. cucumeris* on occasion (Rahman *et al*. 2011a,c, 2012). The biology of *N. cucumeris* and *T. montdorensis* is quite similar, but *T. montdorensis* has been shown to have a higher intrinsic rate of increase than *N. cucumeris* (Steiner *et al*. 2003), and to consume more thrips larvae per day (Vanhouten *et al*. 1995).

Soil predators did not appreciably reduce the numbers of thrips on the flowers or foliage of any host plant tested beyond that of *T. montdorensis* or *O. armatus* released on their own. Therefore, results do not support the release of soil biological control agents to manage WFT on gerberas, chrysanthemums and roses. It is likely that the main reason that soil predators did not contribute to reductions in WFT numbers is due to very low rates of soil pupation. If it can be shown that certain cut flower crops or conditions increase the likelihood of WFT to pupate in soils, then soil predators may become a feasible component in a WFT management plan. It may be possible that manipulation of relative humidity may be used as a management tool. If high humidity can be maintained in a structure (approximately 90%), more WFT may remain on foliage and not seek growing tips or flowers. However, at 90% humidity, relatively few thrips would fall into the soil to pupate, potentially rendering soil predators ineffective (Steiner *et al*. 2011). Potentially, a rapid decrease in humidity when high proportions of L2 thrips are detected on foliage may cause dropping behaviour and soil pupation, and solve this potential issue. In cases of relatively high rates of thrips in foliage, application of foliage predators or a low-risk pesticide may be more appropriate than causing thrips to drop and releasing soil predators.

The pirate bug, *O. armatus*, also significantly reduced the numbers of adults and immatures in flowers and foliage on chrysanthemums, but not gerberas and roses. On carnations, when the numbers of *O. armatus* reached one per flower, the numbers of thrips on unsprayed treatments were half that of treatments that had weekly thrips pesticide applications and few predators (Cook *et al*. 1996). Trials in which *O. armatus* were tested on gerberas and roses were associated with large errors in control treatments (Tables 6,9) and very low thrips emergence across all treatments (Table 9). It is difficult to determine if *O. armatus* does not perform well on gerberas and roses, or if lack of prey or other correlated factors were responsible for the effect.

Conclusion

For the cut flower industry, the results indicate that *T. montdorensis* and *N. cucumeris* are the most effective commercially available predators that provide control of WFT in Australia. *Orius armatus* shows promise for the cut flower industry;

however, further research is required to determine its efficacy compared with *T. montdorensis* and *N. cucumeris*. Soil biological control agents are unlikely to be cost-effective, except perhaps at moderate thrips pressure, on gerberas, chrysanthemums and roses as they did not appreciably reduce the numbers of WFT on foliage or flowers.

Further research is required to determine the differences in the ability of *T. montdorensis*, *N. cucumeris* and *O. armatus* to manage WFT in commercial production situations and to determine the cost-effectiveness of each predator.

ACKNOWLEDGEMENTS

Thanks to Dana Ashford for the numerous hours of spreading sticky goo on traps and counting thrips. Thanks to Leigh Pilkington, NSW DPI, for providing WFT when the culture had to be scrapped and restarted, and Helen DeGraaf and Glenys Wood for advice on rearing WFT. Desley Tree (DAFF Queensland) provided thrips taxonomic training that made this research possible. The lifestyle horticulture team at Redlands Research Facility often gave advice pertaining to various aspects of the project that was much appreciated, with particular thanks to Shane Holborn and Rachel Poulter (both DAFF Queensland). Marilyn Steiner (Biocontrol Solutions), Janelle Dahler, Shane Holborn, Garry Fullelove (all DAFF Queensland) and the *Australian Journal of Entomology* subject editor provided constructive comments on previous drafts of the manuscript. Thanks to Propagation Australia, Gladlands Flower Farm and Shannon Roses for generously providing plants used in the project. Thanks to the funding bodies that made this research possible, voluntary contributors: Flower Association Queensland Inc., Biological Services, Bugs For Bugs (who also generously provided their predators for the project), Ecogrow and Manchil IPM, and Horticulture Australia Limited for providing matched funds from the Australian Government.

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Accepted for publication 9 January 2013.