REVIEW OF ETHYL FORMATE USE IN AUSTRALIA AND POSSIBLE FUTURE USES FOR EMERGING BIOSECURITY RISKS

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Summary

Ethyl formate (EF) is a historical fumigant of dried fruit, with uses extended over time to horticulture and cereal grains. EF is effective against stored product insects and has a synergist effect when applied as a non-flammable EF/carbon dioxide (CO_2) mix on stored grain insects. Additionally, EF is efficacious on horticulture insect pests. EF is an effective bulk grain fumigant with sorption issues being accommodated by rapid dispensing. The lower toxicity EF usually requires relatively high dose (70g/m^3) however its predominant attribute, like methyl bromide (MBr), is short exposure times i.e. hours not days. EF can be used a much lower temperatures than most other fumigants. The volatile and flammable EF is a proven fumigant and a candidate replacement for the ozone depleting MBr. Mixing with an inert gas is required to achieve a non-flammable mixture. Our review found 78 insects that could be controlled by EF, albeit at different rates or exposure times, or in combination with other gases. These insects include five weevils, six aphids, six thrips, seven moths, 18 scale and mealy bugs, and ten beetles. Of these, EF is registered in Australia to control 41 of these pests. The brown marmorated stink bug, Khapra beetle, tomato potato psyllid, tramp ants and other biosecurity threats are good candidates for EF fumigation.

Key words: quarantine fumigation, methyl bromide, non-flammable fumigants, alternative fumigants, food grade fumigant, cool temperature fumigant.

INTRODUCTION

Ethyl formate (EF) is a fumigant used since 1929 to disinfest dry fruits and has a previous history of safe use as a food additive. However, interest in EF as a fumigant declined following the introduction of carbon disulphide and subsequently of methyl bromide (MBr) and phosphine in the 1950's (Ren and Mahon 2006). However, in 2002, carbon disulphide was de-registered for use as a fumigant in Australia (Ren and Mahon 2006). MBr is the fumigant with the widest range of applications (Bell 2000) but was due to be phased out for stored commodities after 2005 (Ren and Mahon 2006). There are restrictions on the use of MBr as mandated by the Montreal Protocol on substances that deplete the ozone layer (TEAP 2000). The phase-out of MBr has drastically increased the use of phosphine (Ducom 2006). Phosphine is the only other commodity fumigant available worldwide but it too is currently under regulatory review in the USA and Europe (Bell 2000). Phosphine has corrosive properties in some circumstances (Maille 2019). Over-reliance on phosphine resulted in a higher frequency of insecticide resistance, unsafe practices and the delivery of grain containing live insects or aluminium phosphide residues (Haritos *et al.* 2006; Ren and Mahon 2006). The use patterns of fumigants continues to change because there are continuing pressures on fumigants due to registration requirements, atmospheric emissions controls, fears on safety or human health, the incidence of resistance. These changes are occurring as the world expects increasingly high standards of pest control in international trade (Bell 2000). Amid these changing circumstances, we examined the Australian use patterns for EF. We propose that the registrations of EF has not kept pace with recent research due to the existing preference for other fumigants. However, there is an increasing number of plant biosecurity incursions (Anderson *et al.* 2017) and there is a need to ensure the registered uses are current to optimise biosecurity needs in Australia. Here we review the science of EF and compare this research with the Australian registered uses.

ETHYL FORMATE BACKGROUND

EF is also known as ethyl methanoate, formic acid ethyl ester, ethyl formic ester and formic ether (Merck Index 1989; Ryan and De Lima 2012). EF is present naturally in soil, water, vegetation, and in a range of plant and animal products. These products include food grains, fruits, vegetables, beer, wine and spirits, tuna, meat, mussels, milk, cheese and bread (Desmarchelier *et al.* 1999; Ren and Mahon 2006; Ryan and De Lima 2012).

EF is a central nervous system depressant (Ryan and De Lima 2012). EF can irritate eyes, skin, mucous membranes and the respiratory system, particularly above 100 ppm (Ryan and De Lima 2012; Safe Work Australia 2019). The gas is weakly pungent at 100 ppm and annoyingly pungent at 1,000 ppm (Safe Work Australia 2019). Agarwall *et al.* (2015) found that EF had a pleasant aromatic odour. EF has the characteristic smell of rum and is partly responsible for the flavour of raspberries (Ryan and De Lima 2014). Commercially, EF is used in the manufacture of artificial rum, as a flavour for lemonade and essences, as a fungicide, larvicide and as an organic solvent (Merck Index 1989; Safe Work Australia 2019). In industry, EF is used as a solvent for cellulose nitrate, cellulose acetate, oils and greases (Ryan and De Lima 2012).

The oral LD_{50} for rats and rabbits is >1,800 mg/kg (Safe Work Australia 2019). EF is not classified as a carcinogen (Safe Work Australia 2019). EF holds "generally regarded as safe" (GRAS) status with the US Food and Drug Administration (FDA) for its use as a food additive (Ducom 2006; Haritos *et al.* 2006). EF has the advantage of a very short fumigation period, low toxicity to mammals and the environment, and a rapid breakdown with minimum or no residues (Coetzee *et al.* 2019; Haritos *et al.* 2006). Some pests are controlled after one hour of fumigation and one hour of venting (Bikoba *et al.* (2019).)

ETHYL FORMATE USES

EF is an old fumigant used on dry fruits since 1929 and has a previous history of safe use as a food additive (Ren and Mahon 2006). Unlike phosphine, EF kills insects rapidly and its residues break down to naturally occurring products such as formic acid and ethanol (Desmarchelier *et al.* 1999; Ren and Mahon 2006). In Australia, there are no MRLs required for EF when used for baled hay, as a fumigant for cereals, pulses and canola and associated storage structures and machinery, as a fumigant for cocoa, and as a post-harvest fumigant of fruit and vegetables (Reuss *et al.* 2001; Ren and Mahon 2006). EF is rapidly sorbed and degraded by most commodities where they have high moisture or are warm (Ren and Mahon 2006). In sorghum for instance, Ren and Mahon (2006) suggested that 20°C was the marginal temperature for EF use to fumigate sorghum.

EF is effective on many horticulture insect pests (Table 1). Additionally, EF is efficacious on stored product insects and has synergist effects when applying non-flammable EF/CO_2 vapour on stored grain insects (Haritos *et al*. 2006). EF was an effective bulk grain fumigant with sorption issues being mitigated by rapid dispensing (Dojchinov *et al.* 2010). EF can be removed from rice products through unforced ventilation (Reuss *et al.* 2001).

There are many registrations for EF across the world. EF is registered in Indonesia, Israel, Malaysia, New Zealand, Philippines and South Korea (Wolmarans *et al.* 2017; Simpson *et al.* 2007). Also, EF is registered in Australia (Table 1). There are three Australian registrations for EF, one as a 98% liquid product and two with EF/CO_2 liquefied gas mixtures (Ryan and De Lima 2014). To minimise flammability, an EF/CO_2 as 1:5 non-flammable mix in high pressure industrial gas cylinders was patented (Ryan and Bishop 2003). Addition of carbon dioxide to the EF significantly enhanced efficacy of the fumigant (Haritos *et al.* 2006). Also, the CO_2 accelerates the penetration of insecticides into insects' spiracles (Ryan and De Lima 2014). Since about 2000, EF was effective in controlling a range of insects (Table 1) in citrus, grapes, strawberries, bananas, sweet corn, stored cereals, pulses, dates and fodder crops (Ryan and De Lima 2014).

Additionally, the Australian Pesticides and Veterinary Medicines Authority (APVMA) has issued permits for EF. Permit 87993 allows for the use of EF for the movement of foodstuffs and general goods to the environmentally sensitive Barrow Island in Western Australia. The application rate must be sufficient to ensure that the concentration over time (Ct) is greater than 270 g.h/m^3. Permit 86953 allows in transit fumigation with EF at 90 g/m^3 for six hours.

Treatment periods are frequently 1-2 hours (Simpson *et al*. 2007; Agarwal *et al*. 2015). EF is efficacious at low fumigation temperatures (e.g. 9.2°C); these temperatures are not recommended for fumigation with MBr or some other fumigants (Tarri *et al*. 2007). Cold (5°C) Navel oranges did not need to be warmed prior to treatment with EF and CO_2 to treat bean thrips (Bikoba *et al*. 2019) hence prolonging fruit shelf life and minimising handling costs and time. Chhagan *et al.* (2013) also treated apricots at 5°C without adverse effect on fruit. De Lima (2011) tested EF successfully in temperatures ranging from 10°C to 20°C.

PHYTOTOXICITY ISSUES

There may be opportunities for the fumigation of live plant matter. EF fumigation of rice (*Oryza* sp.) resulted in no or very low toxicity. EF treatment had no effect on shoot length, germination, low vigour, non-viability or strong development (Reuss *et al.* 2001). EF fumigation did not affect the taste of strawberries (*Fragaria* sp.), odour or decay (Aharoni *et al.* 1980). Additionally, EF caused no significant difference in strawberry firmness, colour, berry damage or soluble solids when exposed to 0.8% EF. However, exposure to 1.6% or higher for 60 minutes caused slight to moderate to severe calyx damage (Simpson *et al.* 2004). In onions (*Allium cepa* L.), there was no effect on the skin colour, onion firmness, incidence of rots and there were no visual signs of phytotoxicity after EF treatment (van Epenhuijsen *et al.* 2007). EF treatment of apricot fruit (*Prunus armeniaca* L.) caused negligible damage (Chhagan *et al.* 2013). In "Thompson Seedless" grapes (*Vitis* sp.), EF fumigation had no significant effect on berry browning, shatter, firmness, bleaching or decay (Simpson *et al.*2007). Banana (*Musa* sp.) colour and firmness were not affected by EF treatment (Sung *et al.* 2009). EF did not result in deleterious effects on fruit quality in navel oranges (*Citrus sinsesis* L. Osbeck) or lemons (*Citrus limon* (l.) Burman f.) (Pupin *et al.* 2013). "Hass" avocado (*Persea americana* Mill.) had skin damage within a week after EF treatment and storage at 5°C, however, there was no effect on skin colour or time taken for fruit to ripen after three weeks of storage and ripening at 20°C (Pidakala *et al.* 2018). For example in mangosteen (*Garcinia mangostana* L.), there was no effect on internal and external quality if treated below 100 g/m^3: calyx, stalk, fruit colour, flesh and odour of treated fruits were no different to untreated fruits (Ormking 2017).

Cut flowers or green leafy material may present some challenges. Sixteen Australian wildflower species were tested with varying doses (Rigby 2018). There were unacceptable phytotoxic effects at higher doses and longer treatment times for six of 10 wildflower products. Phytotoxic effects were eliminated at lower doses and shorter times however insect mortality was unacceptable (Rigby 2018). Similarly, Kim *et al.* (2018) tested EF on 12 different varieties of imported nursery plants. Some plants showed small changes in chlorophyll and colour in post-fumigated plants within the first week but many recovered afterwards. However, there was no recovery in *Spathiphyllum* and *Peperomia* plants. The degree of phytotoxic damage with EF fumigation could depend on species, age, and physical condition when fumigated (Kim *et al.* 2018). EF caused phytotoxicity in 11 or 13 foliage nursery plants (Kyung *et al.* 2019). South African cut Protea flowers were unsaleable after EF fumigation (Huysamer 2018). EF treated celery displayed green leaves turning brown, especially young leaves; older leaves were damaged at higher EF concentrations (Ahmed *et al.* 2018).

A NEW BIOSECURITY THREAT – BROWN MARMORATED STINK BUG

Brown marmorated stink bug (BMSB), *Halyomorpha halys* (Stål), is highly polyphagous and is found on at least 211 plants across 88 plant taxa (Lee *et al*. 2013; Bergmann *et al*. 2016). The biology and ecology were described in detail by Lee *et al*. (2013). Additionally, Lee *et al.* (2013) listed 35 insecticides which provided excellent efficacy against BMSB in field situations.

BMSB is a native of Japan, China, Taiwan and Korea (Lee *et al.* 2013). Subsequently, the pest was found in the Americas in 1990 and spread to Europe (Kriticos *et al*. 2017). BMSB threatens all continents and has the potential to establish in most tropical, subtropical, Mediterranean and warm-temperate climates. These climates include New Zealand, the east coast of Australia, and southern Western Australia (Zhu *et al.* 2012, Kriticos *et al.* 2017). BMSB frequently aggregates in large numbers in sheltered locations to overwinter. These sites include domestic dwellings and the bugs emit a foul-smelling scent when disturbed (Watanabe *et al.* 1994). Other sites include inside and outside of shipping containers used in international trade, vehicles, boats, and machinery moved across borders (Watson 2015).

BMSB has not established in Australia or New Zealand although there were border detections at both countries. The Department of Agriculture, Water and the Environment Australia (DAWE 2020) have a BMSB annual biosecurity risk season with measures applying to imports from September to May each year. In the southern hemisphere, usually BMSB importations occur between November and February, coinciding with late autumn and winter in the northern hemisphere. However, importations are detected in other months. In the period 2004 to 2014, there were 62 interceptions at the border, with 28 interceptions in 2013/14 alone. Source countries included Japan, China, Korea, France and Italy (Watson 2015). Italy emerged as a major source of imports with live insects during 2016-2017 (DAWE 2020).

In 2017 and 2018, there were two separate post border detections of BMSB in New South Wales (NSW) (Horwood *et al*. 2019). Infected premises in Sydney were treated with bifenthrin surface spray and deltamethrin fog (Horwood *et al.* 2019). An incursion in Western Australia was fogged using deltamethrin (Horwood *et al.* 2019). Pesticides for BMSB control in USA was reviewed by Kuhar and Kamminga (2017); dimethoate, malathion, methidathion, bifenthrin, thiamethoxam + chlorantraniliprole, beta-cyfluthrin + imidacloprid and lambda-cyhalothrin + thiamethoxam were reported as the overall most effective pesticides.

EF is a potential BMSB quarantine fumigant. Kawagoe *et al.* (2017) presented data requiring low EF doses (median 10g/m^3, 4 hours) to eliminate BMSB. The LE_{99} (Ct) varied from 20.52 (10.26 mg/L) for 2-hour exposure to 29.29 (2.44 mg/L) for 12-hour exposure. Probit Curve data gave the following LE_{P9} (Ct) of 33.02 (16.5mg/L) for 2-hour exposure, 41.9 (10.5mg/L) for 4 hours and 58.77 (4.9 mg/L) for 12-hour exposure. These results compared to the 70mg/L used in grain fumigation for stored product pests. Also, these results were achieved at 10°C (below the recommended temperature limit for many fumigants). The majority of current MBr fumigation for BMSB are carried out in low density packed containers (e.g. motor cars and associated non-food shipments) which avoids issues of sorption and uniform distribution related to densely packed grain storage. The lower toxicity EF usually requires relatively high dose (70g/m^3) however its predominant attribute, like MBr, is short exposure times i.e. hours not days. On-site mixing with an inert gas is required to achieve a non-flammable mixture. The consumables required to eliminate BMSB at the USDA median 10g/m^3, 4-hours exposure fumigation would be cost competitive with the current MBr treatment. EF can be used in-transit shipping containers and offers savings in labour cost, elimination of the time for a container to remain stationary in a fumigation facility and a significant decrease in time spent between dispatch and receival (Coetzee *et al.* 2019). There were nil detections of EF in the immediate surrounds, up to 15 m downwind or inside and outside of the truck cabin (Coetzee *et al.* 2019). Similarly, EF (90 g/m^3) and nitrogen fumigation of 20ft shipping containers were monitored during an overnight voyage (Coetzee *et al.* 2020). There was no detectable risk to public, crew members on the barge or workers throughout the preceding road journey. Additionally, all tested containers were ready to be opened and unloaded with 5-10 minutes aeration or without aeration on arrival (Coetzee *et al.* 2020). This is a useful attribute for domestic trade.

EXISTING CONTAINER TREATMENTS FOR BMSB

Currently, there are three approved treatment options for BMSB detections at the Australian border in international cargo (DAWE 2020). Heat treatments require that consignments be treated at 56°C or higher at the coldest surface of the goods, for a minimum of 30 minutes or 60°C or higher at the coldest surface of the goods, for a minimum of 10 minutes. Alternatively, MBr is an option with a dose of 24 g/m^3 or above, at 10°C or above, for a minimum of 12 hours (but less than 24 hours), with all start time concentration readings above 24 g/m^3 and a minimum end point reading of 12 g/m^3. Alternatively, a dose of 24 g/m^3 or above, at 10°C or above, for 24 hours or longer, with all start time concentration readings above 24 g/m^3 and a minimum end point reading of 8 g/m^3. Dose increases to compensate for temperatures less than 10°C is not permitted. Topping up with additional fumigant at the end of treatment is not permitted. The treatment has failed if the concentration of fumigant falls below the minimum end point reading at any point during the treatment (DAWE 2020). Generally, PPE clothing is required due to its human toxicity, and MBr recapture is increasingly required due to adverse effects to the environment.

Another fumigant option in Australia is sulfuryl fluoride. The treatment dose is 24 g/m^3 or above, at 10°C or above, for a minimum of 12 hours (but less than 24 hours), with all start time concentration readings above 24 g/m^3 and a minimum end point reading of 12 g/m^3. Alternatively, a dose of 24 g/m^3 or above, at 10°C or above, for 24 hours or longer, with all start time concentration readings above 24 g/m^3 and a minimum end point reading of 8 g/m^3. However, dose increases to compensate for temperatures less than 10°C is not permitted. Topping up with additional fumigant at the end of treatment is not permitted. The treatment in deemed to have failed if the concentration of fumigant falls below the minimum end point reading at any point during the treatment. All these treatments take considerable time and have temperature requirements. These treatments either contribute to greenhouse gases or increasing the carbon footprint of consignments.

Phosphine is registered for farm use in Australia but often requires treatment periods of up to five days (Ren and Mahon 2006). The traditional way to produce phosphine is the reaction between solid formulations of aluminium or magnesium phosphide and an ambient moisture. However, the reaction time varied and relative humidity may cause problems (Ducom 2006). Treatment periods can be as long as eight days. Some of these difficulties can be overcome by the use of cylinder-based formulations which allow the concentrations to build up quickly and reduce exposure periods (Ducom 2006).

OTHER CURRENT BIOSECURITY THREATS

Recently, Khapra beetle (*Trogoderma granarium* Everts) was detected in six stores in Canberra (Evans 2020). Khapra beetle and BMSB are listed as national priority plant pests (DAWE 2020). EF has been demonstrated to be effective against BMSB and Tomato Potato Psyllid (TPP) (*Bactericera cockerelli* Sulc) but use patterns are yet to be registered in Australia. TPP has established in Western Australia and currently, there is a need to treat tomato (*Solanum lycopersicum* L.) seedlings for TPP coming from Western Australia to eastern Australia (Dominiak *et al.* 2020). EF is known to be effective against TPP (Jamieson *et al.* 2015). However, the possible phytotoxic effects against tomato seedlings need to be tested, particularly given the results with cut flowers. Some fumigants kill the seedlings, along with the pest. MBr caused increased rots and browning of green stems on truss tomatoes (Jamieson *et al.* 2015). The low toxicity of EF means that EF could be used for the treatment of living plant matter with minimum phytotoxicity. EF is the only treatment for cut flowers for TPP leaving Western Australia (DAFWA 2017).

Tramp ants are another biosecurity threat. Red imported fire ant (*Solenopsis invicta* (Burren) established in Australia in 2001 and is currently under eradication. In the 19 years since *S. invicta* was originally detected in 2001, A$330 million has been spent on eradication efforts (Queensland Department of Agriculture and Fisheries 2019). Other states maintain surveillance for incursions (Dominiak *et al.* 2010) and regulate product coming from treated areas. For instance, large quantities of hay are moved across state borders during drought periods. Another significant tramp ant is yellow crazy ant (YCA) (*Anoplepis gracilipes* (Smith)). YCA established and was eradicated in two locations in NSW and frequently is found in timber products for milling (Dominiak *et al.* 2011). YCA has established in several areas of northern Australia and these areas still need to transport a range of commodities into southern Australia. EF could be used to treat suspect domestic trade consignments (Lee *et al.* 2019) if EF is demonstrated to be as effective on these other tramp ants. There is a need for fumigants other than MBr to treat these and similar exotic pest detections.

Our review found 78 insects that could be controlled by EF, albeit at different rates or exposure times. These insects include five weevils, six aphids, six thrips, seven moths, 18 scale and mealy bugs, and ten beetles. Of these, EF is registered to control 41 of these pests. There is an opportunity to add more pests to the registered uses based on available science. Also, there is opportunity to evaluate more pests from the more established EF control groups such as thrips, moths and beetles to assist interstate trade.

CONCLUSIONS

Unlike some alternatives, EF kills insects rapidly (Ren and Mahon, 2006). EF has advantages for worker and environment safety (Ren and Mahon 2006); Coetzee *et al.* (2019)). EF is much safer for human use compared to MBr (Ryan and De Lima 2014; Park *et al.* 2020). EF is an effective and less toxic fumigant for horticulture and stored product pests, including during transit on road and sea. Research identified EF as a candidate alternative fumigant for MBr in the elimination of exotic quarantine pests. The effective low dose of EF allows for non-flammable on-site EF mixing to be competitive with the existing MBr quarantine fumigation. In addition, other benefits include environmental release (unlike MBr, EF is not an ozone depletor and has limited life in the atmosphere), occupational (EF TLV=100ppm; MB=5ppm) and the shorter exposure time should reduce facilities costs with potential saving of increased daily fumigations. EF has less onerous requirements for PPE and no recapture technology is required. EF is an attractive alternative fumigant compared with many industry standards.

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Table 1. Some insects of biosecurity concern controlled by ethyl formate. ARU stands for the Australian Registered Use as per registered labels.

Insect	Reference
Aonidiella aurantii (Maskell) – Californian red scale	ARU; Pupin *et al.* (2013); Misumi *et al.* (2013).
Araecerus fasciculatus (De Geer) – Coffee bean weevil	ARU.
Aspidiotus nerii (Bouche) – Oleander scale	ARU; Pidakala *et al.* (2018).
Aspidiotus spp. – Scale	ARU.
Aphis gossypii (Glover) – Cotton aphid	Lee *et al.* (2014).
Asynonychus cervinus (Boheman) – Fullers rose weevil	ARU; Ryan and De Lima (2014).
Bactericera cockerelli (Sulc) - tomato potato psyllid	Jamieson *et al.* (2015).
Caliothrips fasciatus (Pergrande) – Bean thrips	ARU; Bikoba *et al.* (2019).
Callosobruchus phaseoli (Gyllenhal) - Cowpea weevil	Waterford *et al.* (2003).
Carpophilus hemipterus (L.) - Nitidulid beetle	ARU; Finkelman *et al*. (2010); Hilton and Banks (1997).
Carpophilus maculates (Stephens) - Nitidulid beetle	ARU.
Cimex sp. - Bed Bugs	ARU; Busvine and Vasuvat (1966).
Coccus hesperidum (L.) – brown soft scale	Misumi *et al.* (2013).
Cocyra cepholonica (Staint) – Rice meal moth	Asimah *et al*. (2014).
Cydia pomonella (L.) – codling moth	Griffin *et al.* (2013); Jamieson *et al.* (2013).
Cryptolestes spp. - Rusty grain beetle	ARU.
Dasineura mali (Kieffer) - Apple leaf curling midge	Krishna *et al.* (2002); Jamieson *et al.* (2014).
Diaphorina citri (Kuwayama) – Asian citrus psyllid	Wolmarans *et al.* (2017).
Diaspis bromiliae (Kerner) – *Scale*	ARU.
Diaspis boisduvalii (Signoret) – Boisduval scale	Misumi *et al.* (2013).
Dolichotetranychus floridanus (Banks) – Mites	ARU.
Dolochoderus thoracicus (Smith) – black cocoa ant	Ormking (2017).
Dysmicoccus brevipes (Cockerell) – Pink pineapple mealybug	Misumi *et al.* (2013).
Dysmicoccus neobrevipes (Beardsley) – Mealybugs	ARU.
Dysmicoccus spp – Mealybugs	ARU.
Ectomyelois ceratoniae (Zeller) - Carob beetle	Bessi *et al*. (2015).
Epiphyas postvittana (Walker) – Light brown apple moth	ARU; Krishna *et al.* (2002); De Lima (2010); Griffin *et al.* (2013); Jamieson *et al.* (2013).
Esphestia spp - Mediterranean flour moth	ARU; Ryan *et al.* (2006).
Esphestia cautella (Walker) -Almond moth	Asimah *et al*. (2014).
Frankliniella occidentalis (Pergande) – Western flower thrips	ARU; Aharoni et al. (1980); Simpson *et al.* (2004); Ryan *et al.* (2006); Simpson *et al.* (2007); De Lima (2011); Pupin *et al.* (2013); Griffin *et al.* (2013); Huysamer (2018).
Gonipterus platensis (Marelli) - Eucalyptus weevil	ARU; Agarwal *et al*. (2015).
Halyomorpha halys (Stål) – Brown marmorated stink bug	Kawagoe *et al.* (2017).
Helicoverpa armigera (Hubner) – Cotton bollworm	ARU; De Lima (2011).
Helicoverpa punctigera (Wallengren) – Australian bollworm	ARU; De Lima (2011).
Hemiberlesia lataniae (Signoret) – Latania scale insects	ARU; Jamieson *et al.* (2014).
Hemiberlesia rapax (Cormstock) – Greedy scale	Griffin *et al.* (2013); Jamieson *et al.* (2013).
Hypogastrura vernalis (Carl) – purple scum springtails	Ahmed *et al.* (2018).
Iridomyrmex anceps (Roger) – tropical tyrant ant	Ormking (2017).
Lasioderma serricorne (F.) – Cigarette beetle	ARU; Asimah *et al.* (2014); Maille (2019).
Latrodectus hasselti (Thorell) – Red back spider	ARU; De Lima (2015).
Lipaphis erysimi (Kalt.) – Turnip aphid	Lee *et al.* (2014).
Liposcelis spp. - Psocids (Booklice)	ARU.
Liposcelis bostrychophila (Badonnel) – book louse	Deng *et al.* (2010).
Liposcelis entomophila (Enderlein) – book lice	Allen and Desmarchelier (2000).
Macchiademus diplopterus (Distant) – grain chinch bug	Grout and Stolz (2016); Smit *et al.* (2020).
Macrosiphum euphorbiae (Thomas) – potato aphid	Ryan *et al.* (2006).
Myzus persicae (Sulzer) – Green peach aphid	ARU; De Lima (2011); Lee *et al.* (2014).
Nasonovia ribisnigri (Mosley) – Currant lettuce aphid	ARU.
Necrobia rufipes (De Geer) – Red legged ham beetle	Maille (2019).
Oligotetranycus spp. – Mites	ARU.
Opogona omoscopa (Meyrick) – Detritus moth	ARU.

Table 1. (Continued)

Insect	Reference
Oryzaephilus mercator (Fauvel) – Merchant grain beetle	Hilton and Banks (1997).
Oryzaephilus surinamensis (L.) – Saw-toothed grain beetle	ARU; Hilton and Banks (1997); Allen and Desmarchelier (2000); Tarri *et al.* (2007).
Planococcus citri (Risso) – Citrus mealybug	ARU; Sung *et al.* (2009); Misumi *et al.* (2013).
Platynota stultana (Walsingham) - Omnivorous leaf roller	Ryan *et al.* (2006).
Plodia interpunctella (Huubner) – Indian meal moth	ARU; Hilton and Banks (1997); Tarri *et al.* (2007).
Procotolaelaps vandenbergii – Protea itch mite	Huysamer (2018).
Pseudococcus cryptus (Hempel) – Citriculus mealybug	Ormking (2017).
Pseudococcus longispinus (Targioni Tozzetti) – Long-tailed mealybug	ARU; Krishna *et al.* (2002); Ryan *et al.* (2006); Kyung *et al.* (2019).
Pseudocccus maritimus (Ehrhorn) – Grapevine mealybug	Ryan *et al.* (2003); Simpson *et al.* (2007).
Pseudocccus orchidicola (Takahashi) - mealybug	Kyung *et al.* (2019).
Pseudococcus viburni (Signoret) – Obscure mealybugs	ARU; Griffin *et al.* (2013); Jamieson *et al.* (2013); Jamieson *et al.* (2014).
Quadraspidiotus pernicoosus (Comstock) – San Jose scale	Jamieson *et al.* (2014).
Rhopalosiphum maidis (Fitch) – Corn aphid	ARU; De Lima (2011).
Rhyzopertha dominica (F.) –Lesser grain borer	ARU; Allen and Desmarchelier (2000); Haritos *et al.* (2006); Ryan *et al.* (2006).
Scirtothrips dorsalis (Hood) – chilli thrips	Ormking (2017).
Siculobata sicula (Berlese) - Arboreal mite	Grout and Stolz (2016).
Sitophilus oryzae (L.) – Rice weevil	ARU; Allen and Desmarchelier (2000); Damcevski and Annis (2001); Haritos *et al.* (2006); Ryan *et al.* (2006).
Solenopsis invicta (Burren) – Red imported fire ant	Lee *et al*. (2019).
Tetranychus pacificus (McGregor) – Pacific spider mite	Ryan *et al.* (2006); Simpson *et al.* (2007).
Tetranychus urticae (Koch)– Two spotted spider mite	ARU; Krishna *et al.* (2002); Simpson *et al.* (2004); De Lima (2011); Jamieson *et al.* (2013); Pidakala *et al.* (2018).
Thrips imaginis (Bagnall) – Plague thrips	ARU; De Lima (2011).
Thrips obscuratus (Crawford) – New Zealand flower thrips	ARU; Chhagan *et al.* (2013).
Thrips tabaci (Lindeman) – Onion thrips	ARU; van Epenhuijsen *et* al. (2007); Griffin *et al.* (2013); Jamieson *et al.* (2014).
Tribolium castaneum (Herbst) – Flour beetle	ARU; Hilton and Banks (1997); Allen and Desmarchelier (2000); Haritos *et al.* (2006); Ryan *et al.* (2006); Asimah *et al.* (2014).
Tribolium confusum (J. du Val) – Confused flour beetle	Hilton and Banks (1997); Tarri *et al.* (2007).
Tyrophagus putrescentiae (Schrank) – Ham mite	Maille (2019).
Vryburgia lounsburyi (Brain) – bulb mealybug	van Epenhuijsen *et* al. (2007).