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Review

Identifying critical research gaps that limit control options for invertebrate pests in Australian grain production systems

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Abstract Integrated Pest Management (IPM) is often described as a knowledge-intensive approach to invertebrate pest management, requiring information on the biology, ecology and phenology of a pest combined with an understanding of the interactions between crop growth and pests and between pests and their natural enemies. We conducted a systematic quantitative literature review to summarise what is known about pest and natural enemy species common to Australian grain production systems, based on 1513 published and unpublished research studies. Drawing on this information, we address three issues: what are the knowledge gaps in relation to grain pests and their natural enemies, do these knowledge gaps limit the development of an IPM package for grain growers in Australia and what further ecological or biological information might growers require to enhance the use of IPM approaches for managing pests? The main gaps identified include a lack of understanding around specific factors that lead to pest outbreaks or factors that could be useful for predicting when and where pest outbreaks will occur in the future. Monitoring techniques for many pests are not well developed, and therefore, it is difficult to link the density recorded in a field with crop damage and yield loss and to develop economic thresholds that can be linked with intervention decisions. For most natural enemies, the impact in terms of reduction in pest numbers has not been quantified, with very few studies including both pests and natural enemies together. There is large variability in the level of control provided by natural enemies between years and regions, and the factors leading to this variability are not well understood. Finally, the lack of taxonomic resolution for individual species within groups is identified as a critical knowledge gap. We suggest that a more comprehensive fundamental knowledge base is required across the invertebrate community in grain systems aimed at reducing insect pest outbreaks, combined with a greater depth of understanding in monitoring strategies for pests that contribute to pesticide-use decisions.

Key words biocontrol, canola, insecticide, Integrated Pest Management, IPM, parasitoid, predator, wheat.

INTRODUCTION

Integrated Pest Management (IPM) has been successfully applied as a strategy across several agricultural production systems in order to optimise invertebrate pest management, encourage the judicious use of pesticides (to mitigate problems associated with resistant pest populations and environmental contamination) and improve sustainability (Ellsworth & Martinez-Carrillo 2001). Yet there are many systems for which IPM adoption has been slow or piecemeal, and farmers are still heavily reliant on prophylactic application of broad-spectrum insecticides (Zalucki *et al*. 2009; Zalucki *et al*. 2015; Hill *et al*. 2017). IPM has a strong theoretical foundation in the population ecology of herbivores, and especially how herbivore abundance is related to the interactions between bottom-up resources (e.g. crop plant hosts) and top-down mortality agents (e.g. natural enemies). IPM is often described as a 'knowledge-intensive' approach to pest management (Young 2017). IPM may be depicted as a pyramid of knowledge (Naranjo & Ellsworth 2009; Fig. 1), with avoidance techniques at its base, which help to keep pests below economic thresholds. On occasions when pest abundances pass this threshold, knowledge on effective chemical use based on monitoring becomes critical. Underpinning the development and application

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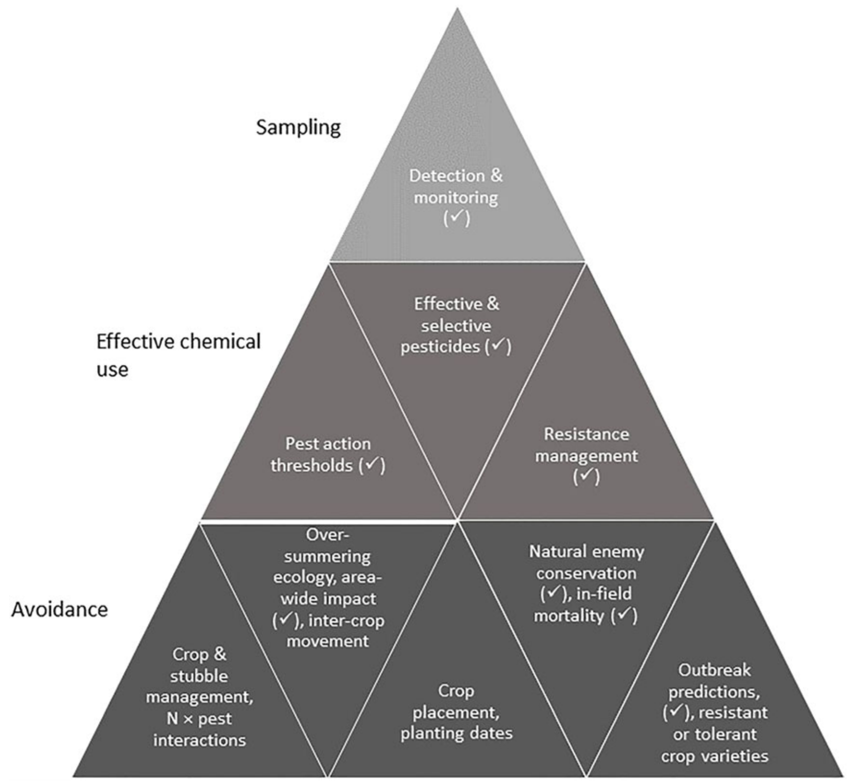

Fig. 1. Conceptual diagram of Integrated Pest Management. The management elements build on each other from the bottom of the pyramid to the top. An example is given of how fundamental ecological knowledge can be used to develop a range of management elements (adapted from Naranjo & Ellsworth 2009). Ticks relate to articles for one, well-studied pest, *Plutella xylostella*.

of pest control measures are fundamental scientific principles of species ecology, population genetics, socioeconomics and crop husbandry (Dent 1995). An IPM approach requires integrating multiple control options and therefore depends on an understanding of how multiple factors interact to determine pest populations. If knowledge of the pest and natural enemy species in a farming system is deficient, IPM programs can be challenging to develop.

IPM is used in some horticultural industries in Australia but has had a slower adoption rate in broad-acre farming industries (Horne *et al.* 2008, see case studies in Zalucki *et al.* 2009). The exception is the Australian cotton industry that has progressively embraced IPM over many years (Wilson *et al.* 2018). In broad-acre grain crops such as wheat, it is difficult to find examples of countries or regions where all the components of IPM have been successfully adopted (Wratten *et al.* 1995). However, at least theoretically, the adoption of IPM should bring some benefits in terms of sustainability. A long-term trial in maize and wheat cropping systems in Europe demonstrated that IPM systems with more diverse crop rotations and less reliance on pesticides were more environmentally sustainable than conventional systems (Vasileiadis *et al.* 2017). In Australian grains, despite a desire to adopt IPM, the unpredictable nature of pest outbreaks and small profit margins have contributed to a high reliance on prophylactic insecticide applications as the sole method for pest control in grain crops (Nash & Hoffmann 2012). Few growers implement practices that mitigate the impact of insecticides on natural enemies (Roubos *et al.* 2014). Some of the more selective pesticides, which are less disruptive to natural enemies, are more expensive and therefore not used commonly (Macfadyen *et al.* 2014), and others are not presently registered for use in grain crops (Umina *et al.* 2015). However, grain growers will face new challenges in the future that may alter how and when they use insecticides. For example, the development of resistance in some of the more widespread pest species will reduce the efficacy of certain insecticides (Umina 2007; Endersby *et al.* 2008; Umina *et al.* 2014), and growers may be forced to use newer, more expensive products. Some pests such as the redlegged earth mite, *Halotydeus destructor*, are now demonstrating resistance to pyrethroids and organophosphates. Given that there are only four mode-of-action pesticide groups in products registered to control *H. destructor* and that resistance against two has been demonstrated, the long-term viability of pesticide-based control options is uncertain (Maino *et al.* 2018). Furthermore, some important pesticide groups (e.g. neonicotinoids) are being deregulated due to human health and environmental risks (Wilson & Tisdell 2001).

We conducted a quantitative literature review on what is known about the pest and natural enemy species common in Australian grain production systems. Given the slow or low rate of adoption of IPM in broad-acre grains, we aim to identify the areas that should be the focus of future research activities of applied scientists working in entomology and ecology. We acknowledge that there are other barriers to adoption of IPM (see

Section Discussion) but focus here on the biological evidence base associated with pest and natural enemy species. We use the literature review to assist in considering three questions of interest. Firstly, what are the knowledge gaps in relation to grain crop pests and their natural enemies? Secondly, which of these gaps in particular limit development of IPM packages for key crop pests and subsequent adoption by the industry? Finally, what is the key biological information required to enhance the use of IPM approaches for managing pests in Australian grains?

MATERIALS AND METHODS

Priority taxa list

We developed a priority list of 44 invertebrate species or taxa considered pests in Australian grain-producing regions (Table S1) to form the basis of our literature search. We use the term 'taxa' throughout as some have yet not been identified down to the species level. For example, the *Bryobia* genus of pest mites likely comprises at least four species, which have been morphologically identified (Halliday 2000; Arthur *et al.* 2010) but are still referred to collectively as *Bryobia* mites in publications. To develop this list, we used databases that have been generated as part of pest alert services offered by cesar (Victoria and New South Wales, NSW, regions), the South Australian Research and Development Institute (SARDI) (South Australia, SA, region) and the Department of Primary Industry, Innovation and Regional Development, Western Australia (DPIRD) (Western Australia, WA, region) (see URLs in the Acknowledgements section). The frequency of reports for each pest species or group was summarised and then ranked. We included species or groups with 10 or more reports (irrespective of their host plants). These taxa occupy Mediterranean and temperate climate zones across the southern and western grain regions and are ranked as some of the most economically damaging pest species (see Murray *et al.* 2013). Stored grain pests and sub-tropical species were excluded from our analysis because they use very different crop hosts and occur in different agricultural landscapes and climate zones. Some pest taxa are native (e.g. Rutherglen bug, *Nysius vinitor*, and native budworm, *Helicoverpa punctigera*), but about half of our list (~55%) are introduced pests. Some other species may have not been included in our list but still have the potential to cause crop damage or be useful natural enemies of crop pests (e.g. *Helicoverpa armigera*, *Mallada signata*). Presently, they may not reach high densities at a local scale or infrequently damage grain crops.

To generate a priority list for natural enemies of grain pests, we used data generated as part of the Pest Suppressive Landscapes project (Parry *et al.* 2015; Macfadyen *et al.* 2015a). This project recorded common pests and natural enemies sampled from crops, pastures, weeds and native vegetation patches in mixed grain production landscapes in southern NSW, southern Queensland and WA over 2 years (Parry *et al.* 2015; Macfadyen *et al.* 2015a). The chosen species were suggested predators or parasitoids of a range of pest species as documented in field handbooks such as Henry *et al.* (2008) and I-SPY manual such as Bellati *et al.* (2018). We removed species recorded only from native vegetation patches, but we retained species sampled from grain crops and pastures. The number of individuals of each taxon per m^2 per site was summed across the samples collected in each region (NSW 756, Queensland 231 and WA 450). We then ranked the natural enemies by those most abundant in Queensland, NSW and WA and included 22 taxa in our priority list (Table S2). The sampling techniques used in this study (beating the vegetation and vacuum samples) were useful for the day-active natural enemies on plants but may have missed ground-active and nocturnal species. Due to the sampling methods, two major groups were missed or under-recorded in this project, namely the spiders and parasitic wasps. For these taxa, we selected a number of families for inclusion in the literature search based on their likely impact on pest species as described in previous studies (Waterhouse & Sands 2001; Pearce *et al.* 2004; Furlong *et al.* 2004b; Tsitsilas *et al.* 2006; Holloway *et al.* 2008; Whitehouse *et al.* 2009; Tsitsilas *et al.* 2011).

Systematic literature review

The literature review followed the systematic quantitative approach outlined in Pickering and Byrne (2014). Original published research articles, unpublished documents and data, grey literature, factsheets and student theses that contained the scientific names of the taxa, and at least one of the categories listed in Table 1 were included. We searched for articles using the electronic databases: Web of Science, Google Scholar, Science Direct and Trove. Searches were conducted from June 2014 to October 2014 (so include articles published up to 2014). Search strings using keywords as wildcards and combinations of pest and natural enemy scientific names or synonyms with topic words were used. For example, '*Nysius vinitor* + life-cycle or population ecology, or abundance'. Combinations of search terms based on the requirements or limitations of each database were used. Cited articles led to additional studies that were also included. To ensure that we only included relevant studies, we screened them based on title and abstract. Studies conducted in Australia in any agricultural context were included (i.e. we did not select only those conducted in grain crops).

We did include unpublished information but focussed on demonstrated evidence as opposed to anecdotal observations. This included data from surveys or field trials and observations of pest outbreaks that were documented. To locate unpublished articles, we communicated with a total of 10 researchers from different states to elicit information. We acquired unpublished articles from SARDI (SA), cesar (focus on Victoria) and DPIRD (WA).

RESULTS

Quantitative literature review

A total of 1513 publications were identified that assessed biological and ecological aspects of the focal taxa. These articles are detailed on the CSIRO data access portal (Moradi-Vajargah *et al.* 2015). A total of 922 publications (Table S3) were related to

Table 1 Categories used to classify articles found as part of the review. Relates to the column headings used in Figures 2–7 and Tables S3 and S4

Category name	Description
Biology	Studies on life-stage development, life-table studies and biological characteristics of the species or individual
Behavioural	Flight, functional response to stimuli and host plant resistance
Physiology	Studies that explored invertebrate digestive, circulatory, respiratory, muscular, endocrine and nervous systems
Insecticides	Impact of insecticides on individuals and populations (both laboratory and field studies)
Population	Population processes, movement, dispersal, sampling, temporal and spatial distribution, ecology, abundance, biological control and distribution of genetic populations
Systematics	Taxonomic studies, identification keys and new species reports

pests and 591 (Table S4) to natural enemies. Many of the articles for pests were linked to more than one host plant type, illustrating the polyphagous nature of many taxa, which, for many species, presents problems across multiple agricultural systems (pastures, horticulture and grains). For the pests, some articles were related to certain host plants (367 articles), but not all were grain crops (166 were focussed on grains; Table S5). For 19 pest taxa (43% of the total pest taxa considered) and 13 natural enemy taxa (59% of the total natural enemy taxa considered), we found five or less articles (Table 2). If the number of articles is indicative of the amount of knowledge surrounding each taxon, we appear to lack even a basic understanding of the ecology and biology of these taxa in the context of Australian systems. We note that some of the pest groups (Table 2) are listed among the top 10 most economically damaging pests in grains: aphids (Hemiptera: Aphididae) rank 7, slugs (Gastropoda) rank 8 and armyworm (Lepidoptera: Noctuidae) rank 9 (Murray *et al.* 2013), and some of these taxa receive relatively high numbers of outbreak reports (e.g. slugs and armyworms, see Table S1). While some additional studies that fit the search criteria have been published since the time of review (2014), this number is relatively small (<10 articles) in comparison to the total publication list and thus do not significantly alter the overall findings. Nonetheless, particularly relevant articles that have been published since 2014 are cited in the following results and discussion.

The lack of taxonomic resolution for individual species within each pest and natural enemy group is a continual challenge. This problem resulted in the lumping of some species into higher-order groups (e.g. all spiders, Araneae), thus limiting the conclusions that could be drawn from simply examining the numbers of articles recorded for each taxon. For example, rove beetles (Coleoptera: Staphylinidae) are a large group of mainly predatory beetles that are often lumped together. Many species are highly abundant in grain systems, but for the genus that is thought to be most common (*Paederus*), we found only three articles (Quinn 1985; Lawrence & Britton 1994; Michaels 2007). Despite these challenges, we summarise the quantitative component of the literature review here for each pest and natural enemy group, and we go on to consider broader issues in Section Discussion.

Pests

The majority of the pest studies were on population and ecological aspects (733 articles). Mites (173), Australian plague locust (123), native budworm (120), aphids (105), diamond back moths (57) and snails (57) had the highest number

Table 2 List of species or groups with five or less articles

Pest	Common name	No. of articles	Beneficial	Common name	No. of articles
Etiella behrii†	Lucerne seed web moth (9–11)	5	*Paederus* sp. (Staphylinidae)	Rove beetle	3
Achyra affinitalis†	Weed web moth (2–15)	5	*Simosyrphus grandicornis*	Hover fly	5
Lipaphis erysimi	Turnip aphid (2–45)	4	*Euborellia* spp.	Earwigs	0
Apina callisto†	Pasture day moth (3–37)	3	Linyphiidae	Spider	3
			Pheidole megacephala	Ants	2
Persectania dyscrita†	Armyworm (26–33)	2	*Rhytidoponera* spp		2
Leucania stenographa†		2	*Chrysoperla* sp.	Green lacewings	3
Ciampa arietaria†	Brown pasture looper (10–30)	1	*Orius* spp.	Pirate bug	2
Forficula auricularia	European earwig (14–23)	5 (incl. 1 as beneficial)	*Dictyotus caenosus*	Brown shield bug	3
Gonocephalum darlingensis†	False wireworm (6–14)	1	*Micraspis frenata*	Striped lady beetle	5
Gonocephalum trivialis†		1	*Coccinella transversalis*	Transverse lady beetle	5
Gonocephalum macleayi†		2	*Coccinella undecimpunctata*	Eleven spotted lady beetle	2
Isopteron punctatissimus†		3	*Adalia bipunctata*	Two-spotted lady beetle	1
Pterolocera spp.†	Grass anthelid (0–10)	3	*Coccinella septempunctata*	Spotted lady beetle	0
Milax gagates	Slugs (7–74)	5			
Deroceras invadens		1			
Arion intermedius		1			
Listroderes difficilis	Vegetable weevil (10–18)	2			
Gonocephalum sp.	Vegetable beetle (7–15)	2			
Cephus sp.	Sawfly (1–11)	0			

The numbers in brackets after the common name indicate the minimum and maximum number of outbreak reports associated with each taxon (see Table S1).
†Species native to Australia (and thus are assumed to have no or limited international publications).

of articles. We summarise the outcomes for major taxonomic groups below.

Aphids and Rutherglen bug, Nysius vinitor

The aphids overall had a much lower number of articles per taxa in comparison to the pest mites (Fig. 2). One of the most common aphids in southern and western Australian cereal crops, oat aphids, *Rhopalosiphum padi*, were relatively well studied with 18 articles. However, no publications could be found on oat aphid physiology, systematics and taxonomy or on impact of insecticides. The articles consisted of mostly population studies (15 articles) and to a lesser extent biology (two articles) and behaviour (one article). Aphid pests of canola, namely green peach aphid, *Myzus persicae* (29 articles), and to a lesser extent the cabbage aphid, *Brevicoryne brassicae* (10 articles), were relatively well studied based on the number of articles alone. The turnip aphid, *Lipaphis erysimi*, had fewer (four) articles (Fig. 2). This disparity is most likely due to the ability of green peach aphid to transmit Turnip yellows virus (syn. Beet western yellows virus), its widespread insecticide resistance and its broad host range across canola, pulse and horticultural crops. The highly mobile hemipteran pest, the Rutherglen bug, *N. vinitor*, was relatively well studied with 29 articles (Fig. 2). However, we still know relatively little about the drivers of sporadic outbreaks of this pest in grain crops.

Pest mites and Collembola

The pest mites (Prostigmata) were mostly in Penthaleidae, with the most well-studied pest mite being the redlegged earth mite (RLEM), *Halotydeus destructor* (Penthaleidae), with 91 articles in different categories (physiology was the only aspect that was not well studied; but see Hill *et al*. 2013; Fig. 2). Another important mite group, the blue oat mites (*Penthaleus* spp.), were also reasonably well represented, with 35 articles. In contrast, we found only nine articles for clover mites of the genus *Bryobia* (Tetranychidae) (Fig. 2). One of these articles investigated the distribution and seasonal abundance patterns of two species of *Bryobia* sp. in southern Australia and found that the species

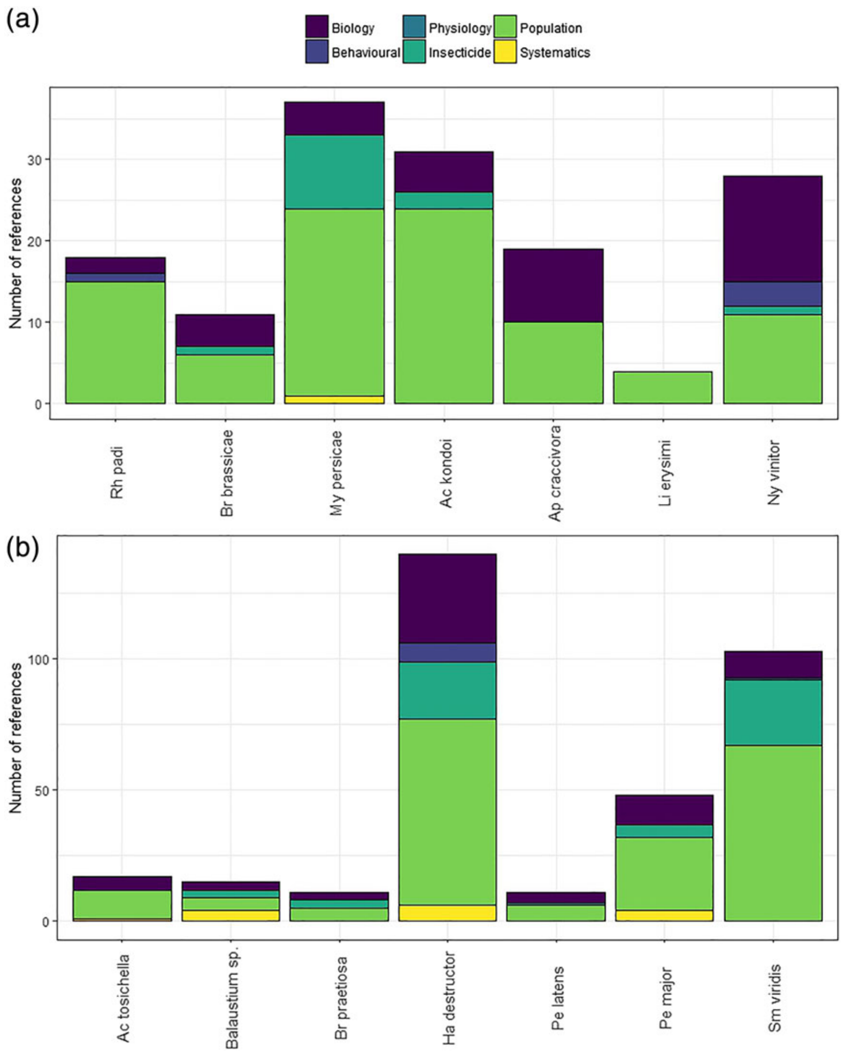

Fig. 2. Number of articles per pest taxon and category found during the literature search for the major pest groups, aphids and Rutherglen bug (a) and mites and Collembola (b). The complete list of all taxa can be found in Table S3. Note that one article may have been counted in multiple categories. For category descriptions, see Table 1.

differed in the number of generations and diapause conditions (Arthur *et al*. 2011). The authors suggested that outbreaks of *Bryobia* spp. and *Balaustium medicagoense* (Erythraeidae) (we found 15 articles for *Balaustium* spp.) have increased over time (Arthur *et al*. 2011), yet they were relatively under-represented in our literature review. There is a paucity of information about *Bryobia* species in grain crops, and very little is known about the distribution, plant host use, diapause patterns and chemical sensitivities of each of the four species. The collembolan lucerne flea (*Sminthurus viridis*), had a significant number of articles (>100 in total; Fig. 2).

Lepidoptera

Of the lepidopterans, the native budworm, *H. punctigera*, and diamondback moth, *Plutella xylostella*, had the highest number of articles (Fig. 3). Those with the fewest articles were the brown pasture looper, *Ciampa arietaria* (two articles), the grass anthelid, *Pterolocera* spp. (three articles), the pasture day moth, *Apina callisto* (three articles), the lucerne seed web moth, *Etiella behrii* (five articles), and the weed web moth, *Achyra affinitalis* (five articles) (Fig. 3, Table 2). Given their global pest status, armyworms are of particular interest. In Australia, multiple species are known by the common name 'armyworm'; however, for this study, we refer only to the four species (Table S1): *Leucania convecta* (accepted name *Mythimna convecta*), *Persectania ewingii*, *Persectania dyscrita* and *Leucania stenographa*. Outbreaks of armyworms were common in the 1980s but have become relatively less frequent over time (Hoffmann *et al*. 2008). However, there are some reports of increased frequency of crop damage associated with armyworms in recent years, but this has not been formally quantified. In total, we found 22 articles for armyworms, but these are not evenly spread such that some species had very few articles (Fig. 3). Articles on *P. ewingii* biology and population factors were the most common in the armyworm group (e.g. Lower 1957; Martyn 1966; Helm 1975; Hill 2013), followed by *L. convecta*. Field studies of *L. convecta*, *P. ewingii* and *P. dyscrita*, and their parasitoids, were conducted in cereals and pastures in Victoria,

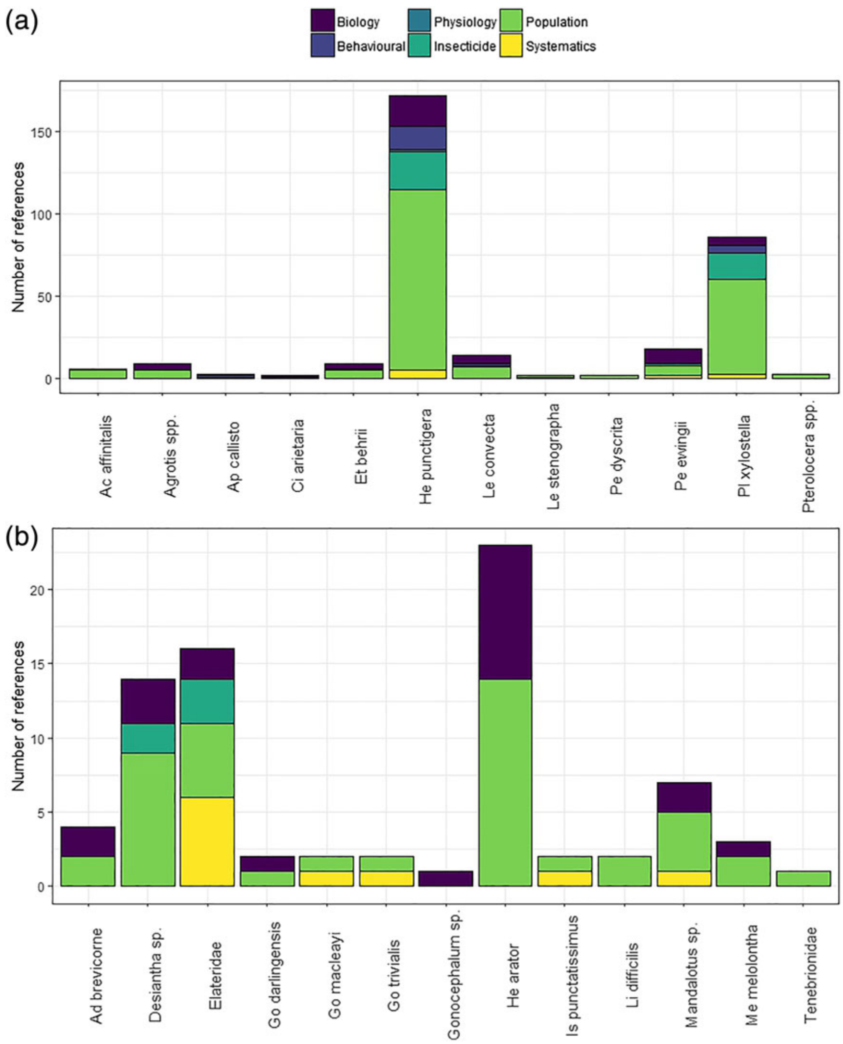

Fig. 3. Number of articles per pest taxon and category found during the literature search for the major pest groups, Lepidopteran pests (a) and Coleopteran pests (b). The complete list of all taxa can be found in Table S3. Note that one article may have been counted in multiple categories. For category descriptions, see Table 1.

Australia, in 1980–1983 (McDonald & Smith 1986). These studies included a survey of the armyworm fauna in the major agricultural districts, detailed phenological observations within five oat crops and ultraviolet light trapping of adults (McDonald & Smith 1986). Large-scale migrations of adult armyworm moths from inland Australia are driven by a range of factors and are likely to be related to pest outbreaks (McDonald *et al.* 1995), but this information has not been integrated into predictive models that may aid in decision making and adoption of IPM practices by growers. Despite these studies, further work is needed to establish the distribution and pest status of each armyworm species in our current grain production landscapes. We cannot currently say how much impact armyworms are having each season, on each crop type; and the current level of risk to growers from each species (including 'armyworms' not considered here) remains unknown.

Coleoptera

Many of the pest beetles in grain production systems have a life stage that exists under the soil surface or under litter and ground cover. Therefore, the life cycles of some of these species can be difficult to characterise, which in turn hinders a grower's capacity to recognise and manage crop damage. This is reflected in the low number of articles found for large groups of multiple species, such as cockchafers (six articles, Fig. 3) and the Elateridae, true wireworms (10 articles, Fig. 3). Similarly, the weevils we assessed including vegetable weevil, *Listroderes difficilis* (two articles), spotted vegetable weevil, *Desiantha* sp. (nine articles), and *Mandalotus* weevil, *Mandalotus* spp. (eight articles) (Fig. 3), had some information but not a consistent number of papers at the species level. Many weevil species may occasionally cause damage in grain crops, and we have a very limited understanding of the distribution and pest status of each species. Furthermore, it can be difficult or impossible to identify the larval stages of each species (Allsopp & Adams 1980), which poses yet another obstacle to the development of integrated management strategies for these pests.

The false wireworm group consists of a large number of species in the Tenebrionidae. It includes vegetable beetles, the genus *Gonocephalum* (six articles), grey false wireworm, *Isopteron punctatissimus* (three articles), and bronzed field beetle, *Adelium brevicorne* (six articles) (Fig. 3). *A. brevicorne* is the most damaging false wireworm species in south and western Australia, but in Victoria, *I. punctatissimus* causes most damage (Miles & McDonald 1999). The life cycle of *A. brevicorne* has been studied in Western Australia (Michael *et al.* 2002), but there is little information on the biology and ecology of this pest in other regions. The true wireworm group consists of multiple species in the family Elateridae, and 10 articles were found for this group (Fig. 3).

Slugs and snails

Out of 55 articles that were collected for snails (four species in total: *Cernuella virgata*, *Cochlicella acuta*, *Prietocella barbara* and *Theba pisana*), the majority focussed on population ecology (Fig. 4). A large amount of research work and management guidelines were synthesised in the 'Bash'Em, Bait'Em, Burn'Em' report (Leonard 2003); however, there are still unknowns, including how to best optimise snail baits and the interaction between stubble management and snail abundance under different soil and environmental conditions. Finally, the impact of natural enemies and other biocontrol agents on snails still requires work. For four species of slugs (*Deroceras reticulatum*, *Deroceras invadens*, *Milax gagates*, *Arion intermedius*), we found only nine articles (Fig. 4), most of which touched on population issues, with one on biology and one on behaviour.

Earwigs, millipedes and slaters

There are many earwig, millipede and slater species that have recently been observed causing damage to grain crops in Australia. The black Portuguese millipede, *Ommatoiulus moreletii*, had the most articles (27), probably due to its status as a nuisance pest in urban areas. Most of these were about the species' population dynamics, behaviour or physiology. Pest slaters (Isopoda), such as *Porcellio scaber*, had fewer articles (seven). More recently, studies have been undertaken to understand the feeding behaviours of some of these pests. In a series of cage experiments, Douglas *et al.* (2017; article not included in the quantitative literature review) documented feeding damage by the slater *Armadillidium vulgare* on a range of pulses, legumes, cereals and oilseed seedlings, but growth stage was important in determining the amount of feeding damage. In contrast, damage caused by *O. moreletii* was limited to lupin, lucerne and canola. Several species of exotic and native earwigs (Dermaptera) present in Australia, with diverse diets, appear to have the potential to be both natural enemies and pests. The European earwig, *Forficula auricularia*, is an introduced species that is considered to be the predominant earwig pest in Australian broad-acre systems (Bower 1993; Quarrell *et al.* 2018), causing damage to several crop types including canola, cereals and some legumes; the study of Hill *et al.* (2019) is a recent modelling study on this species. Despite this, we found only four articles for this species (Fig. 4), with no quantitative research on grain crop damage. *F. auricularia* seems to be increasing in status as an agricultural crop pest worldwide (Sakai 1987; Quarrell *et al.* 2018). There is increasing interest locally, with three articles published in Australia since 2014 (Quarrell *et al.* 2017; Hill *et al.* 2019; Quarrell *et al.* 2018). Earwigs are also described as a beneficial natural enemy in some agricultural systems (see section below); however, factors that lead to them feeding on crop seedlings rather than invertebrates or stubble are unknown.

Natural enemies

Articles on natural enemies mostly reflect biological (207 articles) and ecological (236 articles) factors rather than physiological factors (19 articles) or the impact of insecticides (30 articles). Parasitic wasps (352), spiders (71), carabid beetles (43), lacewings (24) and lady beetles (19) were the top five in the natural enemies group (Table S4). Some of the research

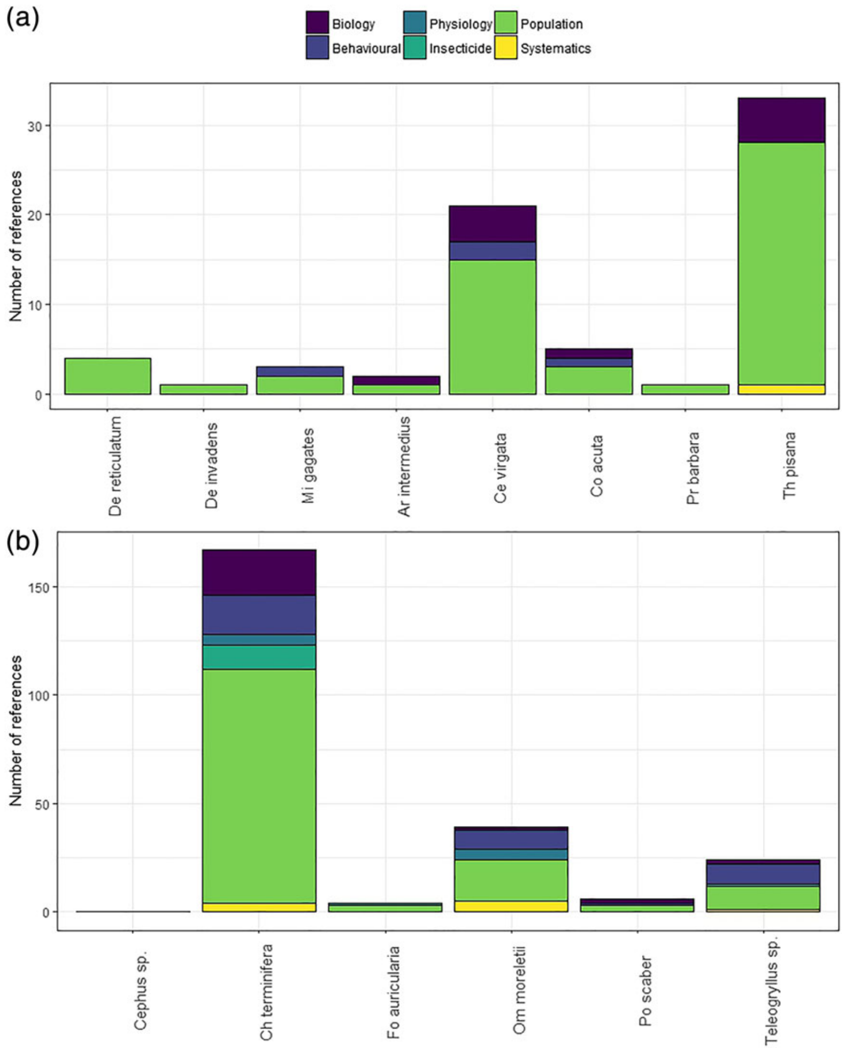

Fig. 4. Number of articles per pest taxon and category found during the literature search for the major pest groups, snails and slugs (a) and 'other' pests (b). The complete list of all taxa can be found in Table S3. Note that one article may have been counted in multiple categories. For category descriptions, see Table 1. *Cephus* sp., sawfly; *Ch terminifera*, Australian plague locust; *Fo auricularia*, European earwig; *Om moreletii*, black Portuguese millipede; *Po scaber*, slaters; *Teleogryllus* sp., black field cricket

gaps identified for each natural enemy group are summarised below.

Spiders

Seven families of free-living spiders (Araneae) commonly occur in Australian field crops, and these were the focus of our literature searches. There were 71 articles (Fig. 5) on these families, mostly focussed on their population dynamics, taxonomy and a few on their biology. These families are a common component of the spider community in cotton crops across Australia (Whitehouse & Grimshaw 2007; Whitehouse *et al*. 2009, 2011; Rendon *et al*. 2015), although their activities in grain crops are less well known. We did not find any information about the impact of insecticides on these spider families. Each family has different methods for capturing prey; Clubionidae are foliage runners, Salticidae and Oxyopidae stalk their prey, Lycosidae are ground runners and Linyphiidae produce tangled webs often at ground level (Whitehouse *et al*. 2009). This means that despite being considered generalist predators, each family will be more likely to contact and attack different pest species, but preferences remain unclear for pests of grain systems.

Predatory mites

Many different predatory mites help control grain pests, and their impact on *S. viridis* is probably the most well-documented interaction (e.g. Wallace 1974; Ireson *et al*. 2001; Roberts *et al*. 2011). Predatory mites belong to a number of different families (Bdellidae, Anystidae, Mesostigmata), and there is no single species that appears to exert overarching control of a pest complex, although studies on these species are few. Only 14 articles were found for the families of predatory mites in Australia, and they consisted mostly of population dynamics (eight articles), biology (four articles) and impact of insecticide (two articles) studies (Fig. 5, Table S4). In Australia, there are native species and a

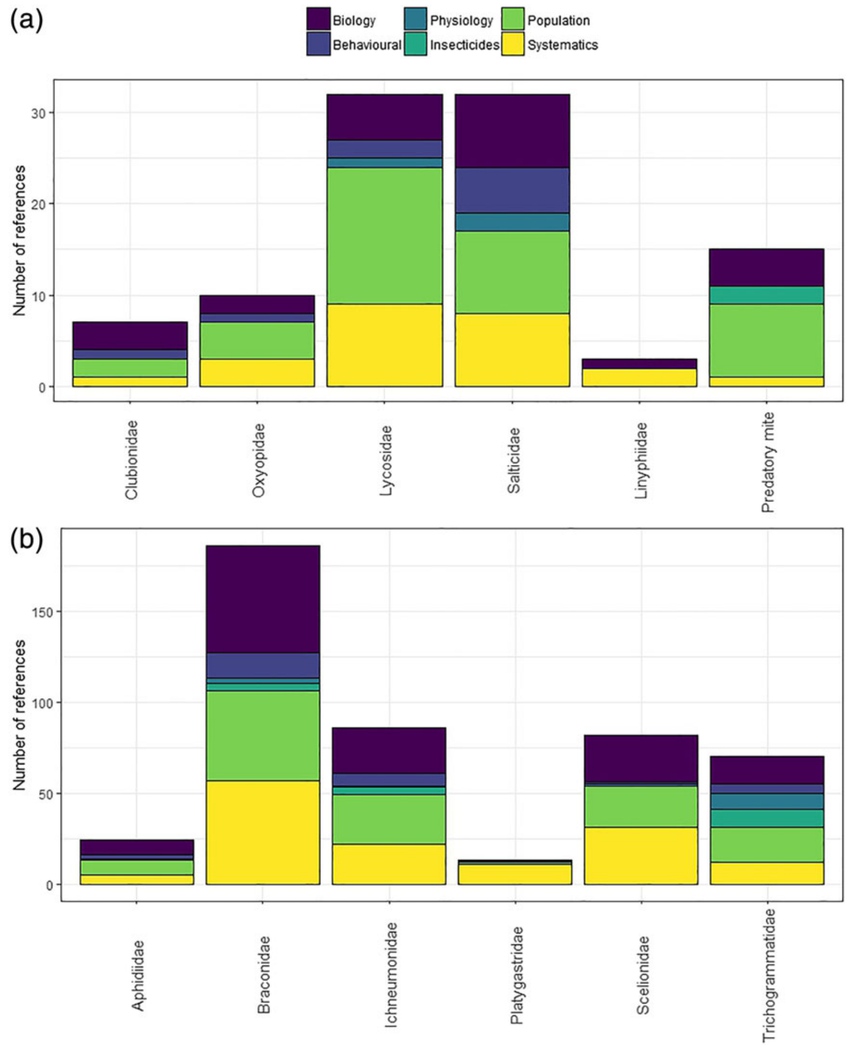

Fig. 5. Number of articles per natural enemy taxon and category found during the literature search, spiders and predatory mites (a) and parasitic wasp families (b). The complete table can be found in Table S4. For category descriptions, see Table 1.

few deliberately introduced species. Perhaps the easiest group to recognise is the Bdellidae, or snout mite (Horne & Page, 2008). The species in this group are all predators and have a characteristic pointed head (Wallace & Walters 1974; Wallace & Mahon 1976). Anystidae species are probably among the more important in cropping and pasture systems. The predatory mite, *Anystis wallacei*, was introduced from France in the 1960s to control *H. destructor* in Western Australia (Otto 1992). The species became established and had a controlling influence on numbers of its prey in experimental releases, but its influence at a whole-field scale is largely unknown (Michael *et al*. 1991; Michael 1995).

Parasitoid wasps

We found a large number of articles related to parasitic wasps (Fig. 5); this may be partially attributed to the search term being at a higher level of taxonomic resolution. Parasitoids of aphid pests (Aphididae) were intentionally or unintentionally introduced into Australia and have since become established (Waterhouse & Sands 2001). We found 21 articles relating to their population ecology, biology and systematics (Fig. 5). Surprisingly, only one article related to insecticide impacts; Franzmann & Rossiter (1981) demonstrated that the survival of *Trioxys complanatus* within mummified aphids varied with 13 different insecticides. Another parasitoid family, the Braconidae, includes a range of important parasitoids that mostly attack lepidopteran hosts, and this family was the most well studied of the parasitoid taxa (151 articles, Fig. 5). Nevertheless, the host range of species from this family in Australia is largely unknown. *Microplitis demolitor* can use a range of native moth larvae as hosts (Seymour 1991), perhaps helping this wasp to persist outside of the growing season. Other resources potentially required to support parasitoid abundance and activity in crops (e.g. floral resources) have been relatively understudied.

Predatory beetles

Lady beetle species (Coccinellidae) are common in grain production landscapes and are thought to be important natural enemies of pests, especially aphids. Surprisingly, relatively few

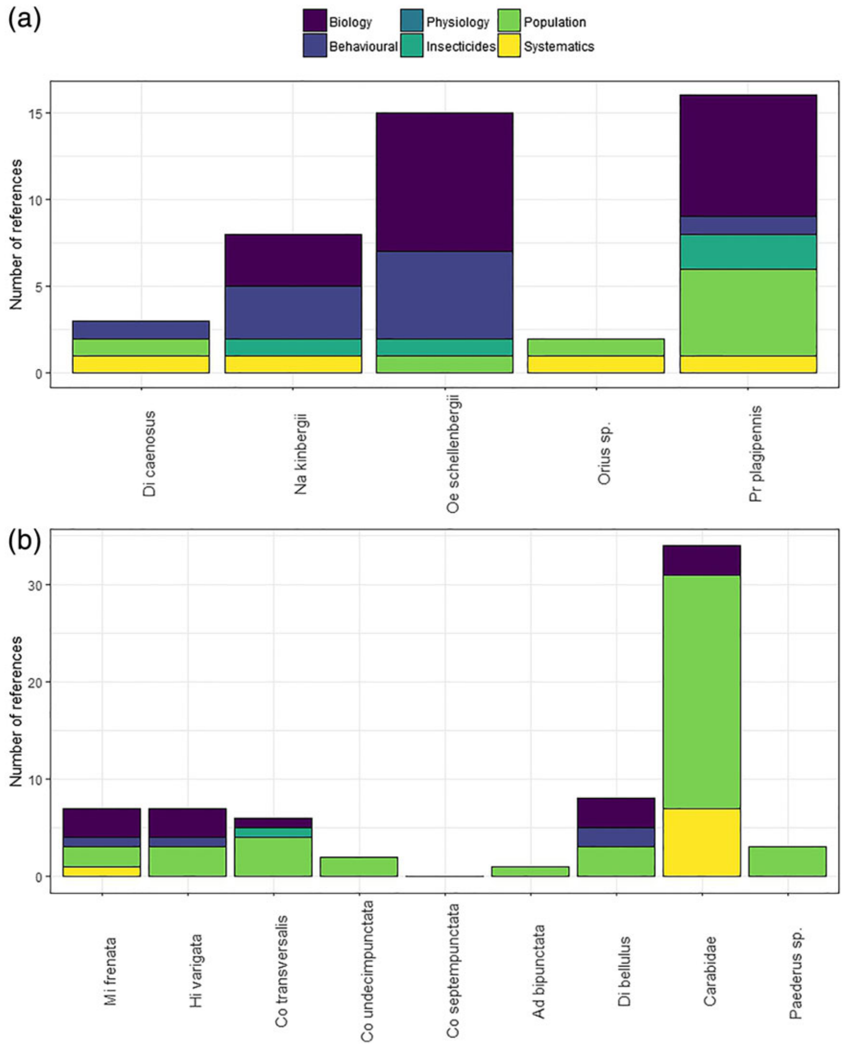

Fig. 6. Number of articles per natural enemy taxon groups, predatory hemipterans (a) and predatory coleopterans (b). The complete table can be found in Table S4. For category descriptions, see Table 1.

articles were found for the six lady beetle species included in our review (Fig. 6, Table 2). The spotted lady beetle, *Coccinella septempunctata* (zero articles), two-spotted lady beetle, *Adalia bipunctata* (one article), and 11 spotted lady beetle, *Coccinella undecimpunctata* (two articles), had the fewest articles (Table 2). Most of the work to date has come from cotton production landscapes (e.g. Mensah 1997) and, to a lesser extent, vineyards (e.g. Thomson & Hoffmann 2013) and brassica crops (e.g. Heimoana 2011). Similarly, the carabid beetles (Carabidae) are known predators of grain pests, but the species that are important for pest control in grains are not well characterised (Nash *et al*. 2008a). We found 43 articles for carabids (Fig. 6), but it is difficult to determine the knowledge gaps due to the fact that these were aggregated to family level. Nash *et al*. (2008b) found that while carabids contributed to control of slug populations, experiments suggest that slug damage was not reduced below economic thresholds by this predator alone. The impact of carabids on other pests remains unclear.

Rove beetles (Staphylinidae) are a large and diverse family with an estimated 900 to >1500 species in Australia (Lawrence and Britton, 1994). Despite this, we found only three articles related to the genus we searched (*Paederus*) (Fig. 6). Members of this family either are predators or feed on dead and decaying matter and live in the soil and leaf litter. There is limited information about which species are important for pest control in grain systems. The largest group of staphylinids in Australia, the Aleocharinae, are predatory, but subfamilies include detritivores (Oxytelinae) and fungus feeders (Scaphidiinae) (Michaels 2007). They are considered important generalist predators in agricultural ecosystems, consuming a range of insect prey including pests of crops (Symondson *et al*. 2002; Thorbek & Bilde 2004). Given the apparent diversity and abundance of this family, more studies are required to generate a basic understanding of its ecology, distribution and role in Australian broad-acre systems.

Predatory bugs

Predatory bugs (Hemiptera) such as the spined shield bug, *Oechalia schellenbergii*, assassin bug, *Pristhesancus plagipennis*, and damsel bug, *Nabis kinbergii*, have been relatively well studied. We found 13 articles for *O. schellenbergii*, 11 for *P. plagipennis* and six for *N. kinbergii* that were mostly focussed on biology, behaviour and population dynamics (Fig. 6). Often, these studies involve feeding assays in simplified laboratory environments. For example, one study showed that *O. schellenbergii* is unable to detect the presence of *H. punctigera* eggs in petri dishes, which in turn has implications for their role as egg predators of lepidopteran pests in more complex field environments (Awan 1983). In addition, juveniles usually failed to capture caterpillars larger than third instars, restricting predation by *O. schellenbergii* to small/medium caterpillars (Awan 1985a, 1985b). While these studies are informative, the impact of the species under field conditions particularly when pesticides are present remains unclear.

A series of studies (Grundy *et al*. 2000; Grundy & Maelzer 2000; Grundy & Maelzer 2002; Grundy 2004, 2007) have assessed the potential of artificially reared *P. plagipennis* in inundative releases for biocontrol in broad-acre crops. In cotton and sunflower, where poor nymph dispersal is likely, the mechanical release of nymphs with vermiculite may be possible but requires further testing (Grundy & Maelzer 2002). Naturally occurring refuges that provide prey and shelter for *P. plagipennis* may allow for the on-farm conservation of this predator during winter (Grundy & Maelzer 2003). Other predatory bugs, such as pirate bug, *Orius* spp. (two articles), and brown shield bug, *Dictyotus caenosus* (three articles), are less well studied (Fig. 6) but could be useful biocontrol agents.

Green and brown lacewings

Green lacewings, *Chrysoperla* spp., are a relatively common predator of a range of pest species, and yet we could find only three articles in Australia related to this genus (compared to 33 articles overseas) (Fig. 7). Adult green lacewings feed on pollen and other insects, and larvae are predatory. Green lacewings are widely distributed across Australian grain production landscapes (New 2002) and have been reported from all mainland states and Tasmania (New 2002). *Chrysoperla congrua* is a widespread species known from parts of northern and central Australia but absent from much of the east and south of the continent. Other green lacewing species in Australia include *M. signata* (not included in this review; Qureshi *et al*. 2010). In contrast to the green lacewing, we found 21 articles related to brown lacewings, *Micromus* spp. (Fig. 7), mostly focussed on their biology, population dynamics and, to a lesser extent, the impact of insecticides. In laboratory studies, brown lacewings were less sensitive than aphids to most insecticides tested (Booth *et al*. 2007). A better understanding of the importance of floral resources and pollen in Australian landscapes for supporting populations of both green and brown lacewings is needed (Robinson *et al*. 2008).

Ants

Ten articles were found for ants (*Iridomyrmex rufoniger*, *Pheidole megacephala* and *Rhytidoponera* spp.) (Fig. 7). All articles focussed on population ecology and were mostly

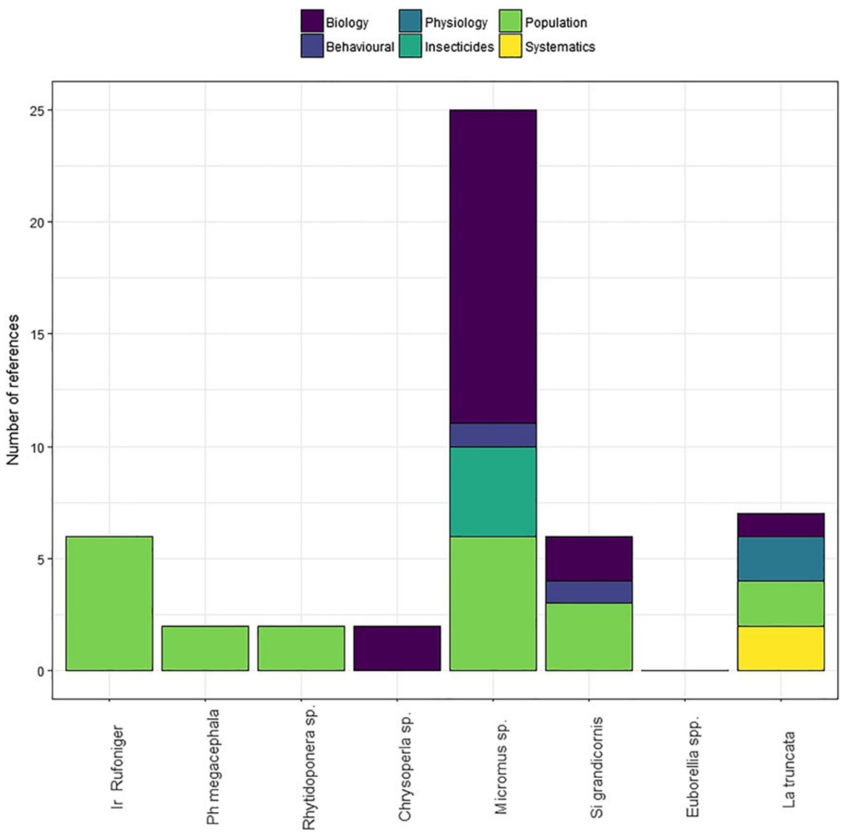

Fig. 7. Number of articles per natural enemy taxon groups, ants, lacewings and other natural enemies. The complete table can be found in Table S4. For category descriptions, see Table 1.

concerned with non-grain host plants; e.g. vineyards (Sharley *et al.* 2008) and grasslands (Gibson & New 2007). Knowledge gaps for ants in Australia exist in many other areas (biology, behaviour, physiology, impact of insecticides and impact on pest species). Ants may increase crop yields under dry climates due to their burrowing activities in soil (Evans *et al.* 2011); however, ants may potentially interact with pest species in ways that are not beneficial to the grower. They may predate important natural enemies of pest species, thereby reducing mortality of pests (Chong *et al.* 2010; Karami-jamour *et al.* 2018).

Earwigs as natural enemies

A total of seven articles were found for the two supposedly beneficial earwig species included in the search (Table S2). Native species, such as *Labidura truncata*, are considered a natural enemy of crop pests (Horne & Edward 1995), whereas European earwigs (*F. auricularia*) can be a pest of grain crops (Hoffmann *et al.* 2008). However, earwigs consume a wide variety of living and dead food and, thus, are considered omnivorous. This breadth of diet means that earwigs can be both beneficial and harmful for farmers. More studies are needed on the predatory capacity of each earwig species under different environmental conditions (e.g. Quarrell *et al.* 2017, a more recent study). For example, *L. truncata* is known to eat false wireworms (Tenebrionidae), pre-pupae and pupae of *Helicoverpa* spp. (Donaldson & Ironside 1982), aphids, cutworms and armyworms (Allsopp & Lloyd 1982), *Teleogryllus commodus* nymphs and *Phthorimaea operculella* (Horne & Edward 1995). The impact of earwig feeding on pest mortality in grain crops is unknown.

DISCUSSION

What are the knowledge gaps?

The scientific literature assembled in our database via a quantitative literature review represents a significant amount of knowledge on pest and natural enemy species in Australian agricultural systems. There are a few important limitations to our approach that impact the findings presented. Firstly, the different levels of taxonomic resolution impacted the numbers of articles found for each taxon. For example, searching on the species '*Microplitis demolitor*' results in far fewer articles than searching on the family 'Braconidae'. For natural enemies that are generally lumped into higher taxonomic levels (Table S2), this can lead to the erroneous conclusion that there are many studies on a group, but this may reflect limited information at the species level. Some relevant articles will have been missed by this review, due to being published in non-indexed journals, lacking relevant keywords or being inaccessible. We have tried to maintain the quantitative nature of this review, so we can compare the relative number of articles between species; however, we acknowledge that some articles may have been missed (especially those published before 1980). We did not assess the comprehensiveness of each article; therefore, a small study is considered equivalent to a more detailed multi-year study in this review. In reality, the usefulness of the content in terms of developing IPM strategies will differ among studies. Indeed, much of the literature is focussed on improving scientific understanding of a taxon, rather than pest management. Studies with management implications are often published in a medium that is not indexed or accessible. Finally, we restricted our searches to the Australian literature, but studies from overseas may be helpful in understanding some aspects of the biology and ecology of taxa (especially introduced species, though note that over half of the understudied pests in Table 2 are native to Australia).

When we compare each group, the numbers of articles are not consistent between taxa, with some taxa lacking even basic knowledge on their ecology and biology (those species highlighted in Table 2). For example, aphids (Fig. 2) had a much lower number of references (zero to 45 references) compared with lepidopteran (Fig. 3) and mite (Fig. 2) pests (zero to 125 and 175, respectively). When we look across all pest groups, most articles addressed some aspects of species population processes such as movement, distribution or abundance in certain locations (79% of all articles for pests, 40% for natural enemies). In contrast, categories such as 'insecticides' only represented 14% of the articles in relation to pests and 5% of articles for natural enemies, despite the current high reliance on pesticides in the grain industry. While we acknowledge that the number of articles *per se* is a crude way of determining knowledge for a given taxon, it highlights taxa and subjects that have received far less research attention.

When we summarise the results across all pest and natural enemy taxa (by examining the summary Tables S3–S5 and Figs 2–7), we identified five important knowledge gaps:

1. Factors that lead to pest outbreaks, or indicate that an outbreak is likely in a certain region, are unknown for many pest species. For aphids, in particular, their relationship with over-summer plant growth ('green bridge') and outbreak risk has not been quantified. Predictive models for outbreak risk of some pests are starting to be developed, but they have not been extensively validated in the field. Such models ultimately require comprehensive empirical datasets, and while these do exist for some species (e.g. the diamond back moth, *Helicoverpa* spp. and various aphids), developing models that are predictive across multiple regions remains challenging (e.g. McDonald *et al.* 2014).
2. Factors that impact species abundance and intermittent pest status of pests such as earwigs, millipedes, certain beetles and slaters are unknown in grain production systems. Some information can be gleaned from urban and orchard systems, but we still do not understand when and why these species become pests of grain crops. Changes in farming practices (e.g. reduced tillage and stubble retention) are widely believed to be driving the increase in these species, yet there are little empirical data on the impact of these practices, or shifts in the pest community within a field in an Australian context.
3. Monitoring protocols for some pests (especially for pests with a below-ground life stage) are not well developed. In some cases, a sampling technique has been used to address a research question, but unfortunately, the technique has

not been further developed into a standardised monitoring protocol. For a few pests, monitoring techniques have been developed, but they are considered too costly or time-consuming to implement (Nansen *et al.* 2015; Severtson *et al.* 2015). This lack of consistent monitoring makes it difficult to link the pest numbers in a field with crop damage and yield loss and to develop economic thresholds that can be linked with intervention decisions.

4. Direct feeding interactions between many pest and natural enemies is lacking from the literature. This means that the impact of most species of natural enemy on pest numbers in fields remains to be quantified. Many techniques are available to conduct impact assessments (Furlong & Zalucki 2010; Furlong 2015; Macfadyen *et al.* 2015b), but these have not been employed in Australian grain systems. Of the species interaction studies that do exist, there is a high degree of variability in the level of control provided by natural enemies between years and between regions. We do not currently understand the factors leading to this variability. The impact of alternative prey, other than pest species, on the ability of natural enemies to suppress pest populations is unclear; however, this is especially critical for generalist predator species.
5. There is a lack of taxonomic resolution for individual species within groups, a knowledge gap that is clearly evident in our compiled list of studies (Figs 2–7). Both spiders and predatory soil mites are examples of natural enemy groups that are poorly defined taxonomically.

Do knowledge gaps limit the development of IPM for grain growers in Australia?

While knowledge gaps are not the only barrier to IPM adoption in Australian grains, they are important in terms of generating control options for pests. If certain pieces of biological or ecological information are fundamental to the development of chemical, cultural or biological control options, then the absence of this information will be problematic. For example, there were a relatively large number of articles that mention sampling and monitoring, information that is critical if pest action thresholds are to be adopted (Leather & Atanasova 2017). Many pests of Australian grain crops lack empirically derived economic thresholds or even basic rules of thumb about what constitutes a yield limiting pest density (see Arthur *et al.* 2014). Simple monitoring protocols that can be used for decision making outside of research are missing for some species; likewise, the development of predictive models to aid in this task is rare (e.g. McDonald *et al.* 2014).

The majority of articles contained keywords relating to sampling and effective chemical use, but 'avoidance' topics, which form the base of the IPM knowledge pyramid, were relatively understudied (Fig. 1). These types of studies generally focus on factors that keep pest populations low or below a theoretical threshold of density, and they do not address what occurs after high densities have been reached. We have taken a well-studied species as an example: *P. xylostella*, which is a pest of canola and other brassicas. We have included ticks in Figure 1 to show parts of the pyramid the 59 articles found in our review relate to (also Zalucki *et al.* 2015). From this research, we can say that *P. xylostella* is difficult to control with insecticides alone because of poor plant canopy penetration with spray equipment, the species' short life cycle (i.e. survivors reproduce quickly) and the evolution of resistance to a wide range of chemical groups (Endersby *et al.* 2008). However, economic impact thresholds in canola, sequential sampling plans (Hamilton *et al.* 2004) and a resistance management strategy (Roush *et al.* 1998) have been developed for this species. Natural enemies can be effective at reducing *P. xylostella* populations (Liu *et al.* 2004; Furlong *et al.* 2004a; Furlong & Zalucki, 2007; Furlong *et al.* 2014), but widespread insecticide use can make them less effective. There is little understanding about the dynamics of predators of *P. xylostella*, but some studies on parasitoids in brassica crops have produced useful information for growers (Furlong *et al.* 2004a). Landscape-level changes in cropping, namely the widespread planting of canola, are likely to have led to increased abundance, with spring catches of migrant *P. xylostella* in Tasmania perhaps acting as an outbreak indicator (see Schellhorn *et al.* 2008). But we do not yet have a predictive model for outbreaks of *P. xylostella* that can be used by growers to predict risk across Australian grain crops; however, Australian researchers have collaborated in developing these tools in China (Li *et al.* 2012; Li *et al.* 2016). The effect of crop cultivar on oviposition preference has only been investigated in vegetable systems (Hamilton *et al.* 2005). The impact of breeding low glucosinolate levels into modern canola cultivars and the interactions with increased crop nitrogen on pest intrinsic growth rates, hence outbreak risk of *P. xylostella*, is poorly understood. The expectation is for lower growth rates in species evolved to feed on brassicas and an increased growth rate of generalist herbivores populations (Giamoustaris & Mithen 1995). For less well-studied pest species (Table 2), the gaps in the IPM pyramid are far more substantial.

Cultural control approaches such as tillage, stubble retention, planting density and crop rotations are all understudied in relation to pest and natural enemy species. Methods like habitat manipulation for increasing populations of natural enemies have received some attention but have not been operationalised in Australian grain production (Bianchi *et al.* 2006; Gurr *et al.* 2018). Furthermore, integration of control options is critical for successful IPM, and some of the knowledge gaps identified may limit this. For example, the lack of information about the impacts of natural enemies on pests (including host specificity for parasitoids), their susceptibility to insecticide applications and the resources they require outside the cropping season all limit the integration of biological control with chemical control options. In order for natural enemies to be used reliably in IPM programs, the field technician requires monitoring techniques and thresholds relative to pest population estimates, which are lacking for all natural enemies of potential significance in the grain industry.

While we have identified these knowledge gaps as being important as barriers to IPM adoption, other challenging barriers exist (Zalucki *et al.* 2009). For example, the benefits of IPM are often not apparent to growers in the short term (i.e. the direct economic savings are small or on par with conventional practice), and often a commitment of multiple seasons is required to achieve observable impacts. The currently available broad-spectrum insecticides are relatively cheap, whereas more selective products (the few that are available) are more expensive. This can contribute to a lack of motivation to change practice when there is no economic incentive. Other barriers to adoption include the poor availability of IPM advisors (Horne *et al*. 2008), and the limited expertise by agronomists regarding how to advise growers on alternative pest management approaches, while managing trade-offs with other enterprise priorities.

What further information is required to enhance the use of IPM in Australian grains?

This review highlights gaps within the current biological and ecological understanding of pest and natural enemy taxa. However, this does not mean that research funds should only be targeted at species with low numbers of articles in this review. Instead, a more comprehensive fundamental knowledge base across the pest community, aimed at avoiding pest issues (Fig. 1, bottom of the IPM pyramid), combined with greater depth of knowledge in specific areas that support the development of IPM approaches, is needed. For each taxon, research needs to target the diversity of control options available to grain growers and therefore facilitate the adoption of IPM. This is especially the case across Australia where there is a seasonally changing complex of pest species that growers need to manage, and a diversity of pest and natural enemy communities in each region.

There needs to be a balance between filling knowledge gaps about resident species and anticipating future pests and novel management approaches. A systems-level approach to generate information about economic thresholds, responses of pests to climatic variability and the long-term impact of management practices (e.g. reduced tillage) on pests and natural enemies need to be explored further. The gaps for natural enemy species are more substantial than for pests, especially around the impact of natural enemies on pests and likely responses of natural enemies to changes in pesticide use.

Similarly, the absence of cultural control options (either by choice or by design) for key pests is a significant barrier to IPM adoption. In some cases, effective cultural control options (e.g. tillage and stubble removal) can disrupt pest life cycles; however, these practices are no longer compatible with no-till systems. Some fundamental practices such as the use of crop rotations, crop choice, timing and density of planting and over-summer weed control were historically used to manage pest population densities across multiple seasons. However, growers do not often consider pest management in relation to these decisions today. Furthermore, traditional cultural control options such as the development of host plant resistance against invertebrate pests in crop cultivars are almost absent from Australian research and development pipelines. We anticipate in the coming years a growth in the development of novel genetic approaches for managing pests, but effective deployment of these approaches in grain landscapes requires a greater understanding of pest species biology and ecology, which is currently lacking for several species. For some of the knowledge gaps identified, there is already established scientific approaches for gathering the information required. Direct investment, specifically in research conducted in Australian grain production landscapes, will help address these gaps. For other gaps, major challenges and impediments to research exist, and they will require a longer-term strategy. The information summarised here will provide a useful context to guide future investment related to pest management research particularly given the dynamic and changing nature of agricultural practices. However, this summary does not address the demand for this research by the ultimate end users, Australian grain growers. We (as scientists) see an increasing need for a more systems-level understanding of pest threats, as evolved resistances, chemical de-regulation, changes to residue limits set by importers and secondary pest outbreaks become more problematic. Growers will increasingly need to take more responsibility for crop protection decisions, with technical support from researchers underpinning a holistic management approach. However, this requires a strong commitment to adopt sustainable pest management practices by the Australian grain industry, and ongoing support for research activities that will achieve this goal.

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SUPPORTING INFORMATION

Additional supporting information may/can be found online in the supporting information tab for this article.

Table S1 Pest species priority list based on frequency of reports (total number) from data gathered by cesar[1], SARDI[2] and DAFWA[3]. A zero indicates the species was not recorded in that regions via this service (although it may be present in that region).

Table S2 Natural enemy taxon priority list identified based on abundance of species in crop and pasture fields over a two year period at sites in three regions (NSW, QLD, WA). Abundance data was collected as part of the Pest Suppressive Landscapes project (GRDC project: CSE00051). A tick indicates the group is one of the most numerically abundant taxa in the samples collected (ranked by total collected for the two years); PR indicates that species was collected but was not common enough to be included in the list of top 20 for that state; AB indicates that species was not present in the state (during the study).

Table S3. Number of articles per pest taxon and category found during the literature search. A total of 918 articles were summarised. Note that one article may have been counted in multiple categories.

Table S4. Number of articles per natural enemy taxon and category found during the literature search. A total of 591 articles were summarised. Note that one article may have been counted in multiple categories.

Table S5. Number of articles per pest taxon found in each host plant category.