Chapter 12

New approaches to manage invertebrate pests in conservation agriculture systems – uncoupling intensification

Michael Nash, Dusty Severtson and Sarina Macfadyen

Invertebrate threats to broadacre agriculture in Australia

A large diversity of invertebrate species has been recorded on broad-acre grain farms across Australia, both pests and beneficials (natural enemies, pollinators and nutrient-cyclers). Many have the potential to cause economic damage, but often do not reach high enough densities, or only infrequently feed on commercial crops. Likewise, some species are considered beneficial in certain contexts but cause crop damage in others (*e.g.* earwigs, Horne and Edward 1995). Overall direct economic losses from invertebrate pests have been estimated at $359 million annually (Murray *et al.* 2013). Factors, such as the evolution of resistance, withdrawal of pesticides from registration and market access, all have the potential to make management of pests costlier.

Changes to management practices, such as the widespread uptake of Conservation Agriculture (CA) (see Chapter 2) have contributed to shifts in pest complexes over the last 30 years (Hoffmann *et al.* 2008, Nash and Hoffmann 2012). The negative perception of increased pest problems in CA contrasts with the potential for increased biodiversity (Loreau *et al.* 2003), ecosystem services (Gurr and Wratten 2004) and increased production (Tilman *et al.* 1996). In this chapter we consider why pests (*e.g.* slugs and snails) may become problems in CA in Australia, or with the intensification of agriculture that is facilitated by CA (*e.g.* aphids). We explore why they become problems for farmers by considering the processes impacting the population dynamics of these species, and new technologies that can help to maintain sound pest management principles within CA systems.

Foundational pest management concepts that rely on invertebrate monitoring

Attributing damage to specific pest species under a variety of management and climatic conditions is difficult given the diversity of potential pest species. Furthermore, conclusively demonstrating that increased or decreased risk of a pest outbreak is due to adoption of one or more CA practices is challenging given the many factors involved. A review by Macfayden *et al.* (2019) concluded *"The ability to predict when and where pests will cause yield loss in grain crops across Australia is limited."* This is due to a lack of knowledge about:

- individual species distribution;
- pest interaction with crop plants, and physiology, that influence population increase;
- the interactions between invertebrate species under different environmental conditions; and
- *ad-hoc* monitoring of invertebrates in broad-acre farming systems

We suggest the attribution of increased pest threats to CA is weak and suspect that in the case of Australian grain production systems, current pest outbreaks are more an issue of availability of resources, mainly moisture (Nash and Hoffmann 2012) and farm labour. That is, broad-acre farmers do not have time to monitor large areas at key times (establishment) and agronomists used for crop scouting are not paid enough to monitor crops more than once a fortnight. Therefore, the population build-up that precedes a pest outbreak is not well documented, and the contributing factors are often not clear.

Integrated Pest Management (IPM) as a concept was pioneered by Stern *et al.* (1959) and adopted in some farming systems in Australia. It is based on an understanding of pest and beneficial dynamics, economic thresholds, monitoring of pest and natural enemy populations to select appropriate control methods, and avoidance of the use of broad-spectrum pesticides. These guidelines have been adopted cautiously by a small proportion of grain growers (Horne *et al.* 2008). Ideally, pest control decisions should take place within the context of the entire agro-ecosystem (Smith 1962), using “sound ecological information about pests and their crop environment” (Kogan 1998). A more limited IPM paradigm, heavily reliant on monitoring and management responses based on thresholds that limit disruption to natural enemies (Dent 1995), has been extended by the Australian grains industry to growers.

Precision Pest Management, is an extension of Precision Agriculture (PA), that makes soil and crop management decisions to fit the specific conditions found within each field (Strickland *et al.* 1998). The accurate and precise application of pesticides made possible within PA aims to reduce over-use, leaching, runoff, and non-target impacts (Brenner *et al.* 1998). This should, in theory, reduce negative environmental effects and thus most importantly improve environmental stewardship (Strickland *et al.* 1998).

Pesticides – are agrochemicals applied to protect crops from weeds diseases and invertebrates. We refer to ***Insecticides*** specifically as agrochemicals that control insect pests, as are other ‘-cides’ for specific invertebrate groups.

The theory versus the practice of CA and pest control

In theory, adoption of CA (Chapter 1 for definition) should lead to reduced crop losses from pests, a reduction in agro-chemical use and, therefore, more profitable farming systems. In practice, pest problems frequently are reported to limit yields in CA systems around the world (Fanadzo *et al.* 2018). If CA is implemented fully, this management approach would include a diversity of tactics to reduce pest populations including:

- use of diverse crop rotations, including cover crops;
- use of cultivars resistant to, or tolerant of, pests;
- careful selection of planting dates (see Chapter 18) and planting density; and
- shrewd use of pesticides (Figure 1).

Crop rotation has been effectively used for many years to break the life-cycles of pests. By planting non-host crops, pests are denied a food source during a critical life stage. However, the diversity in crop rotation choices in some parts of Australia is somewhat limited. Cover crops and crop residues may be important for increasing the populations of natural enemies. However, soil-dwelling pests such as slugs, snails, cutworms and rodents can also benefit from residue retention and therefore prevention from desiccation. Finally, cooler ground conditions due to retained stubble (see below changes to microclimate) cause slower seedling emergence rates allowing pests more time to cause damage to emerging crops. There are many interactions between the adoption of CA practices, the consequences of the change to the crop environment, and pest population dynamics (Figure 1). We illustrate some of these trade-offs and complexities of CA and pest management using specific pest species below.

Specific pest interactions with CA

Slugs and snails Molluscs are associated with farming systems that retain stubble and reduce tillage (Glen and Symondson 2003, Figure 1). Several exotic snail and slug species of European-Mediterranean origin have established in Australia and become significant pests of grain crops (Baker 2002). These include: common white snail [*Cernuella virgata* (Da Costa)], pointed snail [*Cochlicella acuta* (Müller)], small pointed snail [*Prietocella barbara* (L.)] (Hygromiidae), white Italian snail [*Theba pisana* (Müller) (Helicidae)], blacked keeled slug [*Milax gagates* (Draparnaud) (Milacidae)], grey field slug [(*Deroceras reticulatum* Müller) (Agriolimacidae)] (Micic *et al*. 2008), and brown field slug (*D. invadens* Reise)). The main threat from snails is related to market access, with *C. virgata* included in formal import standards (February 2015) for wheat and barley set prior to the China-Australia Free Trade Agreement. The Chinese market is worth AU$1.5 billion (ABARES 2014) to Australia and is estimated to increase the price for barley growers from AU$20 to AU$40 per tonne. Previous contamination issues (*e.g.* Korea 2012) highlight the potential cost snails pose to the grains industry, when a major market restricts access due to a quarantine breach. Slugs are particularly damaging to establishing canola (Gu *et al.* 2007), with yield losses in untreated areas of field trials of up to 80% (GRDC report DAS00134). It has been demonstrated that slug numbers are greater in the absence of natural enemies (Nash *et al.* 2008). The over-use of insecticides and soil tillage reduce the numbers of large generalist predators such as carabid and rove beetles (Nash *et al*. 2008). Therefore, CA systems that reduce negative impacts on beneficial species, in theory should experience fewer problems from slugs and snails due to higher mortality from natural enemies. However, this has not been the experience of many grain producers in Australia, and there are case studies where pesticides have been implicated in crop losses due to slugs (Hill *et al*. 2017).

Green Peach Aphid It has been estimated that, for aphid species found in Australian crops, direct feeding and virus injuries result in potential economic costs of $AU241 and $AU482 million per year, respectively (Valenzuela and Hoffmann 2015). We focus on the green peach aphid [*Myzus persicae* Sulzer (1776) (Hemiptera: Aphididae)] as, economically, it is the most important aphid crop pest worldwide (van Emden and Harrington 2007). Several factors have enhanced its status as a pest, including its wide distribution, host range, mechanisms of plant damage, life cycle, capacity to disperse and ability to evolve resistance to insecticides (Bass *et al.* 2014). Green peach aphid reproduces asexually under Australian conditions and, combined with a short generation time, this allows populations to increase rapidly under favourable conditions to quickly reach damaging numbers (Vorburger *et al.* 2003). In addition, this mode of reproduction has significant implications for population genetics (Wilson *et al.* 2002) and the continuing evolution of insecticide resistance (de Little and Umina 2017). Grain farmers manage the risk of plant viruses vectored by green peach aphid using aphidicides; either seed treatments or sprays once the crop has emerged. The control of green peach aphid on many crops has relied almost exclusively on the use of chemicals, with intensive use over the last 50 years leading to the evolution of widespread and multiple forms of resistance (Bass *et al.* 2014). Resistance is now confirmed for most classes of aphidicides registered for use in Australia, including the organophosphates, carbamates, pyrethroids, and neonicotinoids (Umina *et al.* 2018). Insecticide resistance management strategies (IRM) that are implemented by agricultural industries, are essential if the utility of current and future insecticides is to be preserved (Sparks and Nauen 2015). We believe CA practices can provide growers with a production system that facilitates the shift away from intensive agro-chemical usage, thus mitigating current threats posed by pests that evolve quicker than the development of new chemical classes and pesticide products. However, to achieve this the adoption of CA practices needs to be uncoupled from the use of pesticides and implemented with IPM.

Pest management remains one of the greatest challenges for the adoption and continued used of CA practices and, in most farming systems, the adoption of CA practices leads to greater use of agro-chemicals. Although CA does not automatically necessitate the greater use of pesticides, this may arise where integrated pest or weed management is not practised within the CA system and therefore a heavy reliance on pesticides exists (Figure 1). Often full adoption of CA is unlikely to occur (or only partially occurs) in situations where there is little or no access to cost-effective pesticides that work. For example, in small-holder farms across Africa the adoption of CA practices has been low due to limited access to pesticides to prevent losses from pests, especially weeds (Thierfelder *et al.* 2018). In contrast, in systems with easy access to low cost pesticides (*e.g.* Australia), over-use has exacerbated pest issues through resistance evolution (Gould *et al.* 2018) and secondary pest outbreaks (Hill *et al.* 2017) due to loss of natural enemies.

Other factors that lead to variable outcomes in relation to CA practices include time since adoption and how this interacts with the response of individual species to the removal of tillage. It may take some years for populations of pests in a no-till (NT) field to increase to a level where they ultimately cause crop damage. Even then, it may only be in specific environmental conditions (*e.g.* warm, dry) in which pests feed on crop plants. Furthermore, both pest and natural enemy species can respond differently to tillage. For example, Marti and Olson (2007) recorded more aphids, ants and ladybeetles with less tillage, while lacewings, spiders and fungal pathogens showed no difference between tillage treatments. Petit *et al.* (2017) showed that cereal fields that adopted CA over four years prior had high abundance of beneficial, predatory carabid beetles. These examples suggest that CA should lead to benefits for farmers, but this is not always the case. For example, Brainard *et al.* (2016) in the US, showed in a vegetable system that complete adoption of CA resulted in greater pest and cover crop management costs.

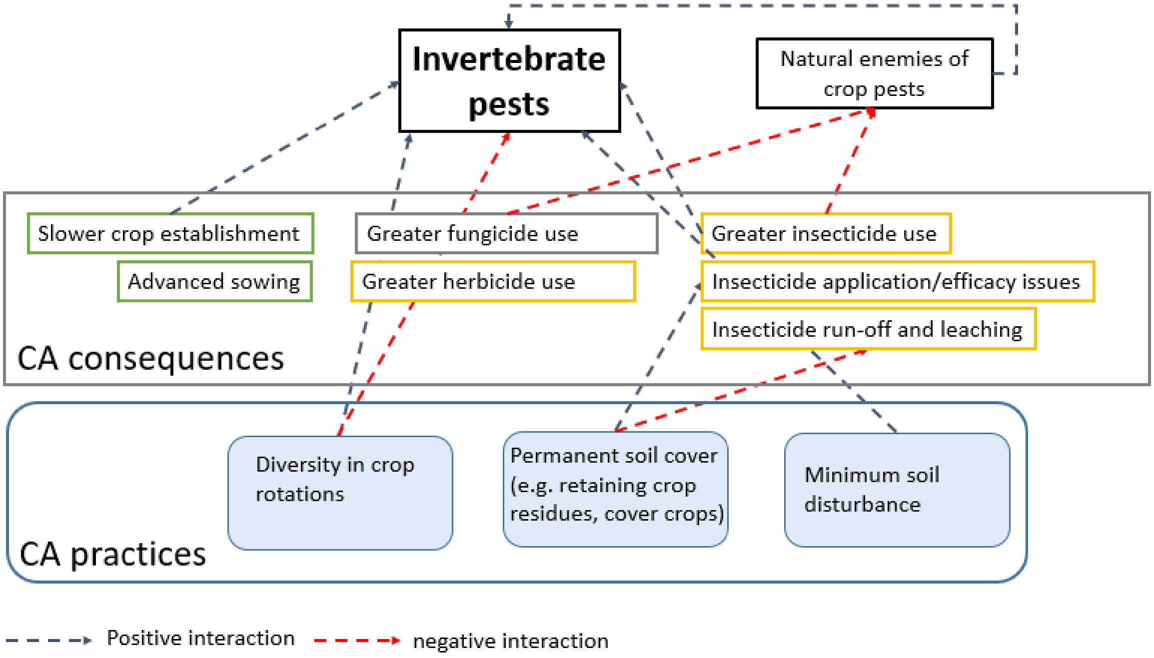

Figure 1. The potential impact of conservation agriculture on invertebrate pest management. Note that the conservation agriculture practices themselves and other changes to the system that often occur in response to adoption both have impacts on pests and natural enemies

Changes in crop environment and how they interact with CA and pest management

Changes in climate and microclimate

Along with increased adoption of reduced tillage and stubble retention, there have been fundamental changes to climate, crop rotations used by farmers and pesticide use patterns. These may all interact and impact pest populations. Efficient water use is critical to the success of dryland farms in water limited environments, *i.e*. most areas of Australia (Nash and Hoffmann 2012). Likewise, many Australian invertebrate pest species have become adaptive strategists that can use and respond successfully to low and unpredictable water resources (Greenslade 1983). The influence of climate change on pest species has been examined in various farming systems (Thomson *et al.* 2010, Macfadyen *et al.* 2018), with a consensus that there will be a change in species threatening crops, not only between seasons but over longer timeframes. Farm management continues to respond to climate change generating the ongoing need for adaptive management of pests in this context (Sutherst *et al.* 2011).

Retaining stubbles influences the microclimate experienced by invertebrates through cooler soil temperatures (Malhi and O'Sullivan 1990), and therefore slower establishing crops (Figure 1). Slow crop establishment leads to seedlings being exposed to herbivory for greater periods of time (Gu *et al.* 2007). In the case of pest-sensitive crops such as canola (*Brassica napus*), IPM recommendations often include:

- selection of cultivars that have vigorous seedling growth (*e.g*. hybrid cultivars);
- sowing larger seed (canola >2 mm); and
- avoidance of some seed treatments that slow establishment (*e.g*. Cosmos® BASF containing fipronil 500 g/L).

Conversely, stubble retention aids moisture conservation near the soil surface (Monzon *et al.* 2006) enabling crops to be sown earlier (see Chapter 18). Early, dry sowing, due to a less reliable seasonal break and autumn/winter rainfall decline (Cai and Cowan 2013), has some benefits for crop growth:

deeper roots, improved seedling vigour in warmer soils, greater weed competition, greater radiation interception and reduced evaporation have all been recorded.

Crop establishment in conservation agriculture

Timely application of pest control during a busy sowing program can be problematic. Growers are therefore naturally drawn towards cost effective prophylactic application of agro-chemicals (Nash and Hoffmann 2012). For example, pest earth mites (*e.g.* red-legged earthmite, RLEM [*Halotydeus destructor* (Tucker)]) are generally considered a key establishment pest of canola (Gu *et al*. 2007), yet Umina *et al.* (2015) only observed significantly greater yield in one small plot experiment in a canola field, out of a total of four experiments. Hill *et al*. (2017) found no benefit in applying miticides despite pest mite presence in a south west Victorian field and lower numbers of carabid and rove beetles were observed in areas treated with a broad-spectrum insecticide, resulting in subsequent higher slug numbers. However, overall yield responses were not conclusive (Hill *et al.* 2017). That study highlights that growers often ignore invertebrate communities when considering sowing times; yet changing planting date would reduce canola exposure to pests at the key establishment stage. For example, slugs become active in mid-May when canola has been sown traditionally; with soil moisture above 25% v/v canola seedlings are more susceptible to herbivory and slower to establish than when sown in April. The current shift to earlier sowing of canola crops in Australia has enabled them to establish quicker and be at a less susceptible growth stage (*i.e.* GS 1.4-1.6) by the time slugs become active (M Nash *personal observations*). Conversely, early sowing of canola, in April, may lead to increased risk of virus transmission due to actively migrating green peach aphids (Henry and Aftab 2018).

Current pesticide use-patterns

Theoretically, the adoption of CA practices should not necessitate greater use of pesticides. In practice, adoption of NT can lead to a greater reliance on herbicides to control weeds, and in some cases a greater use of insecticides and fungicides in response to greater pest populations (Figure 2). Over the last 30 years, an increase in use of low cost agro-chemicals has been observed (Gould *et al.* 2018) across large geographic scales. The challenge is to support growers to limit inputs, enabling them to take advantage of premium markets that stipulate low or below detectable minimum chemical residue limits (MRLs) in products. In line with international trends, data compiled from the Australian Pesticides and Veterinary Medicines Authority (APVMA) suggest an increase in total agricultural chemical sales, year on year, of AU$40 million. Specific pest reports in relation to adoption of CA are not clear. However, some pests have increased in association with pesticide use with the worldwide trend of agricultural intensification (Tilman *et al.* 2002) through reduction in biodiversity and biological control (Geiger *et al.* 2010). To understand further if the ecosystem service of pest control by natural enemies is being maintained in CA first we must answer the question: Has insecticide usage in Australia increased since the inception of CA in Australia?

To examine the changes in insecticide usage in Australia expenditure records from APVMA are presented in Figure 2. Total expenditure in Australia for 2016/17, to protect all agricultural crops from invertebrate pests, including horticulture, grazing and broadacre, was AU$613 million. There has been a decline in insecticide sales since the early 2000s, due in large part to insecticide reductions applied to cotton to control cotton bollworm following release of GM Bollgard II® cultivars in 2003. At this time, selective insecticides were available, economic validation occurred, and an industry-wide extension campaign led to widescale adoption of IPM in cotton (Wilson *et al.* 2018). If data prior to full uptake of new cotton technologies are excluded (Bollgard II®), then expenditure on insecticides has increased since 2006/07 by AUD$20 million, year on year (Figure 2). APVMA data support previous studies that suggest that pest control in arable farming systems is still reliant on broad-spectrum insecticides (Nash and Hoffmann 2012, Macfadyen *et al.* 2014); many growers have not adopted IPM despite heavy investments into research and extension by the grains industry (Macfadyen *et al.* 2014) and the ever-increasing threat of resistance (Umina *et al.* 2018).

Despite mites (Acari: Penthaleidae), including red legged earth mite and blue oat mite [*Penthaleus* spp.] being considered a significant pest in pastures and other broadacre enterprises (Murray *et al.* 2013), miticide expenditure has declined since 1999 by AU$1 million year on year (Figure 2). The extremely variable expenditure (AU$15,149,239-AU$72,632,850) is most likely due to these pests causing economic damage only occasionally; often control is not required (Hill *et al.* 2017).

Insecticides are applied as seed treatments to prevent damage from aphids, which transmit viruses and suppress mites, and lucerne flea activity [*Sminthurus viridis* (Collembola: Sminthuridae)]. The APVMA data suggest that expenditure on seed treatments has remained relatively stable across time (Figure 2). However, expenditure jumped in 2016/17 by AU$17 million (34%) and remained so in 2017/18, despite a decrease in the price growers paid for imidacloprid, the dominant insecticide applied to seed, and fluquinconazole, a fungicide applied to canola seed, due to generic products becoming available on the Australian market. We suspect the increased expenditure is in response to imidacloprid being applied to cereals to protect plants from the Russian wheat aphid (Kirkland *et al.* 2018), which first appeared in Australian cereal fields in 2016 (Yazdani *et al.* 2018).

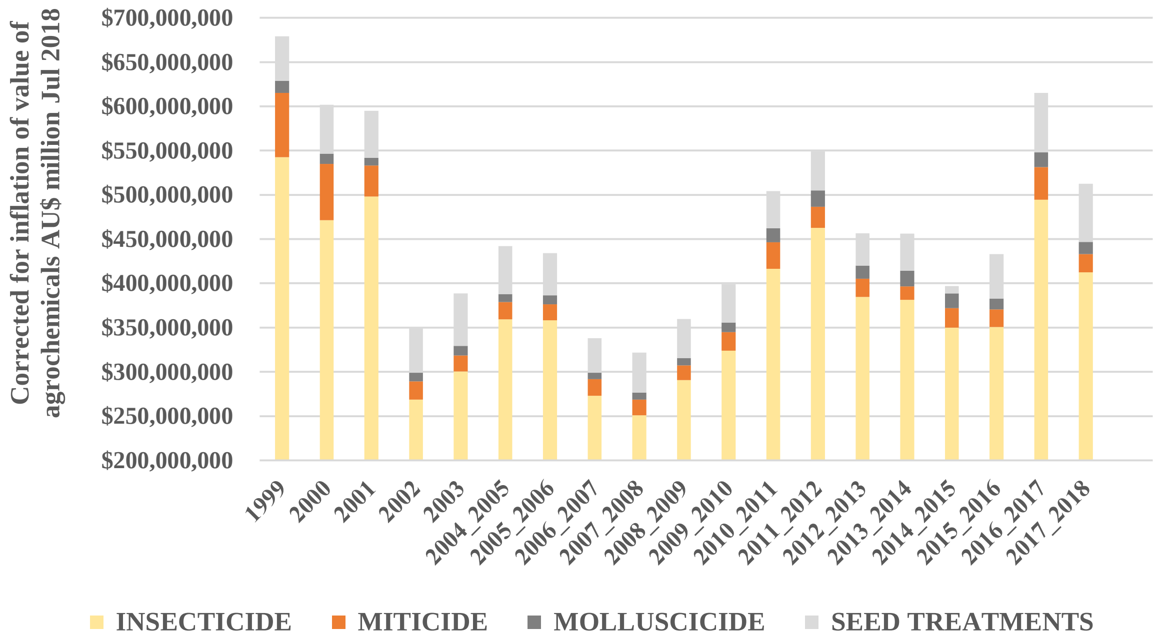

Figure 2. Value of pesticides applied to protect crops in Australia from Invertebrates presented as a yearly breakup of agricultural chemical sales into various APVMA classes (APVMA data accessed 28 Mar2019) since 1999, corrected for inflation. Note reporting of data changed in 2003 from end of year to end of financial year. Drought occurred in many regions of Australia from 2001-2009

Molluscicides applied to control slugs and snails are separated in the APVMA data, and expenditure has increased consistently across time (Figure 2). We believe slugs and snails are adapting to the adoption of CA and, in some areas (*e.g.* south west Victoria), are forcing growers to use tillage and burning for cultural control of these pests. The impacts of over-reliance on pesticide application in biological communities (Geiger *et al.* 2010) in fields managed under CA needs to be separated from invertebrate responses arising from CA (see Figure 1). Otherwise this may lead to dis-adoption of CA in contexts where changes to pesticide use alone may have beneficial effects.

Solutions to pest challenges in conservation agriculture

Along with the adoption of CA over the past four decades (see Chapter 2), there has been an increasing reliance on broad-spectrum synthetic insecticides to protect crops from economic damage caused by arthropod pests (Macfadyen *et al.* 2014, Figure 2). However, the evolution of resistance and the non-target impacts to beneficials have led to advances in pest management tactics; *i.e.* strategies that target pest species and minimise adverse effects on non-target species (Horowitz and Ishaaya 2013). Several studies have demonstrated that the adoption of sampling plans for pests in field crops has led to a reduction in pesticide usage and improved pest management (Serra *et al.* 2013, Stubbins *et al.* 2014). It is important that broad-acre farmers in CA systems realise the value of this new suite of monitoring and decision support tools to manage pests sustainably. The rise of digital technologies (see Chapter 24) will aid farm management generally, although we only consider technologies specific to monitoring pests here.

Pest patchiness

Van Helden (2010) described the spatial and temporal dynamics of arthropod pests in arable crops in the context of precision pest management. Spatial heterogeneity of arthropod distributions in field crops are driven by a wide range of factors including plant phenology, *e.g.* leaf age (Kennedy and Booth 1951) and growth stage (Ferguson *et al.* 2003), as well as land topography (Hill and Mayo 1980), distance from crop edge (Severtson *et al.* 2015), host plant chemistry (Nowak and Komor 2010) and host plant sensory cues (Powell *et al.* 2006). An example of this spatial variability at the field level is provided in Figure 3. In a single field in Western Australia we measured, at a fine resolution, canola plant density and plant growth characteristics, as well as the spatial distribution of multiple aphid species. The distribution of cabbage aphids and green peach aphids differed between pest species and by sampling technique (visual inspection on leaves and racemes and sweep netting – Figure 3vi-xi). The patterns seen across the field (Figure 3) show strong edge effects where aphids were more abundant around the edge of the field. This information could be used to the advantage of the field operator by targeting pest scouting to areas where the arthropod pests are most likely to occur first.

Characterisation of spatial distribution patterns of arthropod pests in large-scale agricultural fields is important because it affects the sampling effort needed to estimate their population density. Some methods include Spatial Analysis by Distance IndicEs (SADIE), the sequential probability by ratio test (SPRT) and geographic information systems (GIS). SADIE was developed to detect and measure the degree of heterogeneity in spatial patterns of insect populations (Perry 1998); it has been used to identify factors which determine their spatial distribution (Ferguson *et al.* 2003, Cocu *et al.* 2005) and to improve sampling plans for pests in crops (Nansen *et al.* 2005, Reay-Jones 2014, Severtson *et al.* 2016). The SPRT has been employed to develop sequential sampling plans with reduced sampling effort and increased accuracy compared with fixed sample size methods (Severtson *et al.* 2016). GIS and geostatistics have also improved understanding of the spatial patterns of insect pests and their influence on sampling and optimisation of insecticide application (Liebhold *et al.*1993, Dmini *et al.* 2010).

Remote sensing to improve monitoring

While manual sampling of arthropod pests is crucial to identify infestation levels, recent advances in remote sensing technology may provide methods to automate detection of plants experiencing pest-induced stress. Furthermore, advances in insect trapping technologies provide early warning of pest migration into crops before or while the insects are being colonised. Knowledge of the timing of the arrival of low densities of colonising aphids can be important to prevent the spread of crop diseases vectored by aphids, and to target surveillance activities to the fields that have been colonised.

Since the emergence of precision agriculture in the mid-1980s, technologies such as global navigation and satellite systems (GNNS) and GIS, as well as improved computing systems, have led to the site-specific or variable rate application of products, especially fertilisers (Gebbers and Adamchuk 2010). These technologies have allowed farmers to move away from ‘blanket’ or whole-of-field application of single-rate fertilisers to site-specific, variable rate application so that products are applied where they are required. Significant cost savings associated with reduced fertiliser inputs drove this technology to adoption. Site-specific or variable rate application of insecticides or other control methods have potential for similar reasons, particularly if arthropod pests can be detected early before populations cause economic damage or when minimal insecticide is required to target smaller areas of infestation. These early infestations could also be targeted with release of biological control agents. However, significant challenges to identify the arthropod pest species has slowed the development of variable-rate insecticide applications based on pre-defined GIS files produced from canopy reflectance data acquired from remote sensors (*e.g.* drones or satellites).

Jones and Vaughan (2010) explained how abiotic (such as water stress or mineral deficiency/toxicity) and biotic stress (*i.e.* pests and diseases) cause similar responses in plants; *e.g.* decreased chlorophyll content, altered growth/biomass and stomatal closure. Classification of the plant canopy reflectance data from the main sensor platforms (thermal, spectral, fluorescence, multiangular, lidar and microwave) has been successful and with good accuracy, but the stressed plants detected often required ground-truthing to diagnose the causal agent. Diagnosing the causal agent in pest management programs is important as many arthropod pests in agriculture require insecticides with different modes of action and rates of product; more than one arthropod pest species may be present.

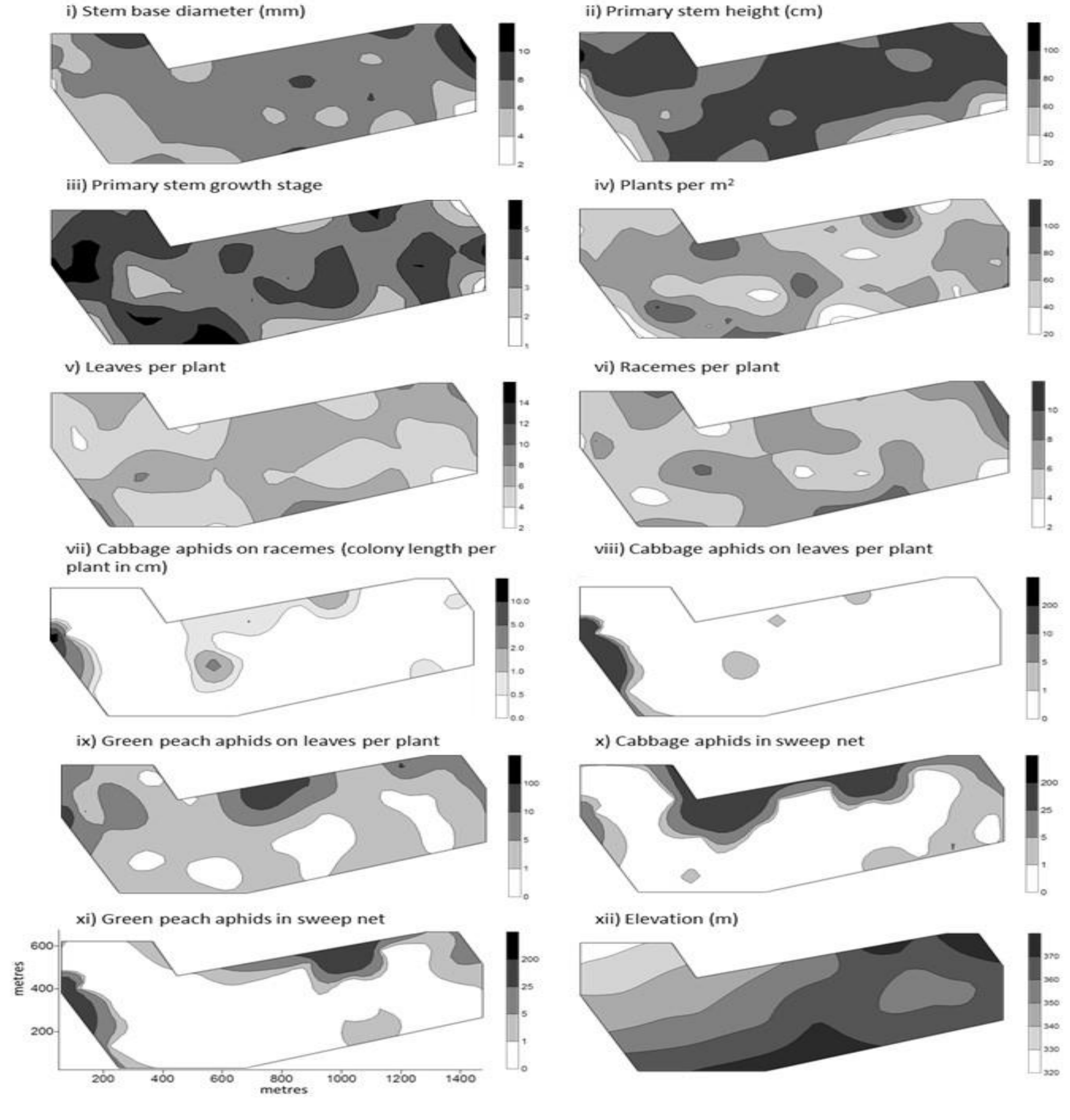

Figure 3. Spatial patterns seen in a large single field of canola near York, Western Australia, August 2013. The maps show the spatial variability in a number of factors related to plant phenology(i-vi), cabbage aphid abundance on plants and in sweep nets (vii, viii, x), green peach aphid abundance on plants and in sweep nets (ix, xi), and elevation across the field (m asl)

Machine learning and artificial intelligence may provide useful outcomes in terms of detecting specific pests responsible for plant stress reflecting complex spectral signatures without the need for ground validation (Bouroubi *et al.* 2018). Nonetheless, canopy reflectance data, such as Normalised Difference Vegetation Index (NDVI), can target pest scouting and crop monitoring efforts to parts of the crop which are experiencing stress. This is most likely to be infested with a pest, disease or other causal agent which can be strategically ground-truthed. Such targeted crop scouting of stressed regions ultimately increases detection accuracy by accounting for spatial aggregation of arthropod pests and reduces the labour required to scout field crops.

Smart traps – agriculture utilising digital technologies

Another type of technology aiding crop monitoring and decision support for arthropod pest management in CA has been termed 'smart' trapping. Smart trapping often refers to some sort of technology which is 'smarter' than a traditional manual method of trapping such as:

- The Limacapt (Anon. 2019a) system helps to count and monitor the activity of slugs throughout the night. This tool, which is more efficient than manual refuge traps (Archard *et al.* 2004), enables highly detailed analysis of the risks caused by this pest and hence provides information to enable more informed decision-making;
- The DTN Smart Trap® (Anon. 2019b) uses established pheromone lures for specific pest moth species and traditional sticky material housed within a delta-type trap. It is enhanced using remote imaging infrastructure with deep-learning algorithms to detect pests in near real-time and transmit the information via existing telecommunications networks to mobile and web platforms; and
- The Trapview® (Anon. 2019) uses a similar infrastructure with imaging and automated pest detection using algorithms and comprises a sticky conveyer belt that can be moved remotely to reveal a new round of sticky paper.

Together with remote pest detection and automated counting, predictive models are being developed which quantify the risk of caterpillar damage using the temporal moth counts and climate data. These digitally based technologies are considered a breakthrough in monitoring of highly variable pest populations when labour for scouting is limited.

Pheromone traps

The development of pheromones and semiochemicals, which attract specific insect species, has greatly improved the way field technicians trap pests (*e.g.* moths) and provide presence data as an early warning as the pest migrates into crops (El-Sayed 2018). Pheromone trapping has the benefit of being species-specific thereby saving time on specimen sorting and diagnostics. However, some groups of arthropod pests such as aphids require manual trapping via suction traps or sticky traps; this brings with them a suite of other arthropods that require sorting and diagnostics. To improve field intelligence and decision support around temporally targeted insecticide application (or not to apply in low risk scenarios), engineers have developed in-field molecular diagnostics machines which rapidly diagnose aphid species and the presence of viruses they vector prior to the aphids colonising the crop using their nucleic acids. One of these new technologies is called Loop Mediated Isothermal Amplification (LAMP). It has been used successfully to detect from yellow sticky traps green peach aphids and turnip yellows virus (TuYV) in the aphids as the canola crops were being initially colonised, providing growers with information on the risk of virus epidemics (Congdon *et al.* 2019).

Increased diversity in cropping systems

The benefits of plant diversity relative to strict monoculture include improved pest suppression and increased pollination services leading to increase yield. In some environments, mixed species cover cropping may offer a new approach in the Australian context to increase biodiversity. Previous research has focused on increasing landscape heterogeneity (Schellhorn *et al.* 2008, Thomson and Hoffmann 2010), often through the provision of diverse 'shelterbelts' (Tsitsilas *et al.* 2006). Provision of services from small margins into relatively large fields needs to be questioned, and the value of in-field resources quantified further (Nash and Hoffmann 2012). Previous research indicates biodiversity needs to be provided within productive landscapes at relevant spatial scales to provide pest control. For example, in viticulture planting of native plant species between vines improved pest suppression (Danne *et al.* 2010); pollination services from bees placed every 200 m within faba bean crops increased yield by 17% (Cunningham and Le Feuvre 2013); and the inclusion of habitat for predators within UK fields improved pest control, *i.e.* beetle banks (Thomas *et al.* 2002). However, in Australia, when plantings were not at the appropriate scale beetles were not found to be greater in abundance, whereas other predators such as spiders increased (Tsitsilas *et al.* 2011). More research is needed to understand the value of increasing biodiversity for Australian farmers under the context of cost benefits for pest management and other ecosystem services.

The inclusion of polycultures, such as inter-cropping or cover cropping, may have multiple benefits under Australian conditions where fields are large, and there is a need to diversify crop cultivars, type and flowering time to minimise the risk of crop failures in dryland systems (Nash and Hoffmann 2012). An example of intercropping is the practice of sowing canola and peas together (peaola), which has been successfully used in higher rainfall zones of Australia since the 1980s and is receiving attention again (Fletcher *et al*. 2016). The growing of mixed species crops that are not harvested for grain, known as cover cropping, is a key component of some farming systems overseas (Sarrantonio and Gallandt 2003), but is yet to be adopted widely in southern Australia, mainly due to the water used by the cover crop reducing the following cash crop yield. A variant of this is pasture cropping where cash crops are sown into established native pastures, but significant impacts on grain yield reduced gross margins, but also lowered input cost and risk associated with crop failure (Millar and Badgery 2009). Historically the sowing of cereals (*e.g.* oats or barley) as cash crop into mature lucerne stands to compete with grass weeds has anecdotally been used successfully in mixed farming systems across southern Victoria and parts of NSW, but again yields are often reduced (Harris *et al.* 2007). However, few studies have linked the increased crop diversity to pest suppression or reduced risk of pest outbreaks. In one such study, there was a reduction in the number of times economic thresholds for heliothine caterpillars were exceeded in crimson clover and rye was less compared to control plots. The build-up of predators in the cover crops subsequently resulted in reduction in the level of heliothines in no-till cotton (Tillman *et al.* 2004). The provision of increased crop diversity must be quantified to link the perceived benefits of pest control to both economic and environmental outcomes.

Concluding remarks

To increase grower acceptance of invertebrates in fields, a greater understanding is required of crop damage under different management practices, and the resulting impacts on yield. The benefits provided by invertebrates can be harnessed to decrease agro-chemical usage, increase water infiltration, nutrient cycling and pollination of pulse crops, whilst improving access to premium markets. For growers to harness the benefits of CA they must also have knowledge of, and access to, a diversity of pest management approaches. Here we have outlined some of the solutions to the pest management challenges created by (or the consequence of) CA practices, including novel monitoring approaches, smart traps and ways to increase crop diversity. We emphasise that the adoption of CA practices in theory should not necessitate the greater use of pesticides, although in practice this trend is occurring in Australian systems. Uncoupling these intensification practices from CA practices is the next challenge.

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