Barriers to IPM adoption for insect pests in New Zealand pastures

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Abstract

New Zealand's pastoral sector faces significant challenges to pest management as long-standing insecticides are deregistered. To protect their pastures, farmers need to shift from reactive responses that lead to poor economic outcomes to pre-emptive responses that are viable in the long term. Current management practices (insecticides, endophytes, biological control) for New Zealand's pasture insect pests were assessed from the perspective of Integrated Pest Management (IPM). Potential impacts from novel control strategies and emerging digital technologies were evaluated to determine how these could improve pest management. Cryptic IPM is present within the New Zealand pastoral sector: that is, farmers practise various elements of IPM but these elements are not integrated into a cohesive system, so farmers often fail to recognise pest impacts until significant economic losses have occurred. We identified important networks by which farmers, industry and researchers communicate and share information, and can develop strategies to raise awareness of IPM. To encourage adoption, farmers need to feel ownership of pasture IPM. Investment in IPM training for farmers through industry extension networks is essential to prepare farmers for the shift away from chemical insecticides to new biologically based control methods. Adoption of IPM will help pastoralists respond to current and new pest challenges.

Keywords: integrated pest management, pasture pests, biological control, adoption, damage thresholds

Introduction

New Zealand's pastoral industry is worth an estimated $17.3B annually in dairy, meat and fibre production for domestic and export markets, representing over 70% of gross agricultural production (Anon. 2016). Healthy and productive pastures are the foundation of these livestock systems; however, pastures are under threat from destructive insect pests (see Ferguson et al. 2019 for a recent review). Poor pasture persistence is also recognised as a significant problem across all sectors of the pastoral industry, particularly where weather conditions, such as drought, and insect pest pressure occur simultaneously (Zydenbos et al. 2011; Morrison 2017). Another significant challenge for the pastoral industry is the availability of chemical pesticides to manage destructive pasture insect pests as commonly used organophosphate insecticides are being reassessed and deregistered (New Zealand Environmental Protection Authority 2013; 2019). The importance of environmental stewardship is acknowledged by the pastoral sector (Morrison 2017) at a time of increasing intensification for New Zealand farming (Parliamentary Commissioner for the Environment 2004; Ministry for the Environment & Stats NZ 2019). To protect their pastures in the future, farmers will need to shift from reactive responses based on chemical insecticides to pre-emptive responses using new control options that are effective as well as environmentally safe and sustainable in the long term. Such a shift will lead to better economic outcomes because farmers will be able to act earlier to prevent significant pasture damage and the associated production losses, which were quantified by Ferguson et al. (2019).

A framework that would assist this shift in focus for pasture insect pests is Integrated Pest Management (IPM). IPM has been recognised for a long time as an effective pest management strategy (Hoskins et al. 1939; Stern et al. 1959, Kogan 1998) that is still relevant today (Hoddle 2006; Walker et al. 2017; Wilson et al. 2018; Lowe et al. 2019). The aim of IPM is not to annihilate pests, but to manage them below economic thresholds using a range of methods including cultural and biological techniques. An economic threshold is the point at which a pest starts to decrease the profitability of the crop (Lowe et al. 2019). A well-functioning IPM system is one where the system is so well managed that pests rarely need direct control. Due to its popularity, however, the term IPM has been used indiscriminately.

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IPM has been used to refer to specific tools used in IPM systems or even to describe insecticide rotation systems (Ehler 2006; Peterson et al. 2018).

Despite all the interest, IPM systems are difficult to establish and maintain because they are more complex than other pest management systems (Lowe et al. 2019). An IPM system consists of a toolkit of techniques used to control pests incorporated into a framework that involves: 1) management practices to reduce the chance of pests exceeding their economic threshold; 2) monitoring potential pests to identify if or when pests need additional control; and 3) if the threshold is reached, selecting a control technique from the toolkit that conserves beneficial species (predators, parasitoids, diseases) and maximises impact on the target pest (Kogan 1998). The establishment and maintenance of such a system requires a large support infrastructure that includes information providers who test how and when to apply tools and monitor pests, and methods of sharing relevant information, either through formal extension officers, or more informally through farmer groups.

An IPM approach was undertaken by the New Zealand pastoral sector to manage the fungus that causes facial eczema in livestock. The response included: monitoring spore levels in pasture; changing grazing practices to reduce livestock exposure to spores; fungicide applications to pasture; treatment of livestock with zinc; and selective breeding of livestock to increase genetic resistance (Di Menna et al. 2009). The apple export industry in New Zealand has also transitioned successfully to an IPM system to meet market requirements for high quality produce with minimal pesticide residues (Walker et al. 2015). Pastoral insect pests are often managed using broad spectrum insecticides, with approximately 79 tonnes of active ingredient applied to pasture in 2004, comprising mainly organophosphates and carbamates (Chapman 2010). It is difficult to quantify current insecticide use because New Zealand has no national database for recording pesticide use (Hoddle 2006), but the number of organophosphate and carbamate active ingredients registered for use in pasture has declined from twelve in 2010 to nine in 2019 (Chapman 2010; Young 2019). Diazinon has label claims for six pasture insect pests and is scheduled for deregistration by 2028 (New Zealand Environmental Protection Authority 2013; Young 2019). Chlorpyrifos and maldison (both organophosphates) and alpha-cypermethrin (a synthetic pyrethroid) with label claims for ten pasture insect pests altogether, are all scheduled for review (New Zealand Environmental Protection Authority 2019; Young 2019). A solution to the loss of broad-spectrum insecticides is to transition the management of pastoral pests to an IPM system.

Transitioning to an IPM system is difficult. The Australian cotton (*Gossypium* spp.) industry nearly collapsed in the late 1990s because of insect pressure. Over the previous 20 years consecutive insecticides aiming to annihilate the key pest, the moth *Helicoverpa armigera*, had instead caused it to develop resistance to each insecticide so that, by 1998, it had developed resistance to all the insecticides used to control it (Fitt et al. 2009; Wilson et al. 2018). As annihilating pests had not worked, the cotton industry changed tack to an IPM system. It was able to do so because: 1) it developed an industry-wide network of extension officers to provide advice on IPM and to be a conduit for new information on IPM techniques; 2) there was an extensive toolkit of selective insecticides available and alternative techniques to insecticides including insecticidal transgenic Bt cotton (that had been available since 1996); and 3) the industry established a network of Area Wide Management groups where farmers discussed concerns and supported each other (Wilson et al. 2018). The adoption of IPM by the Australian cotton industry is one of the most successful adoptions of IPM in broad-acre cropping worldwide. As such, it is a good benchmark in the development of an IPM system for the New Zealand pastoral industry.

This paper focuses on how existing pastoral insect pests in New Zealand could be managed using an IPM system, expanding on ideas drawn from the Australian cotton industry. The discussion below outlines which elements of IPM are already present in New Zealand's pastoral sector; identifies key barriers to systematic adoption of IPM by pastoral farmers; and explores potential solutions to remove these barriers.

Discussion

IPM elements present in the New Zealand pastoral system

The goal of IPM programmes is to create an environment that keeps pest populations below economic thresholds with minimal need for additional control measures such as insecticides (Hoddle 2006). Successful IPM programmes have: 1) a large toolkit of pest-specific control methods available to reduce pest populations below economic thresholds; 2) effective monitoring systems; 3) informed farmers and/or farm advisors, who are aware of the different control options and the key decision points, which leads to widespread adoption by farmers in a region or sector. Successful IPM programmes also need to be fit for purpose, practical, responsive to farmers' needs (i.e. every pest that a farmer may encounter is included in the programme), and adaptive to each farmer's situation (i.e. the programme includes cost-benefit analyses for high through to low value markets serviced by the target crop).

The current New Zealand Pasture IPM toolkit

Pastoral farmers already use a range of pest control tactics in New Zealand: chemical insecticides, biological control using parasitoids and pathogens, plant resistance primarily through endophyte-infected cultivars, and cultural control practices to crush pests underground or to conserve insect pathogens during pasture renewal. A summary of control options and key references is given in Table 1 and Ferguson et al. (2019) provides a review of pasture pests including control options. For example, caterpillars from a group of native moth species in the genus *Wiseana* (collectively known as porina) are pests that can be controlled by a wide range of measures including endophyte-infected cultivars of ryegrass (*Lolium* spp.) (Popay et al. 2012), naturally occurring pathogens (Fleming et al. 1982), and a selective insect growth regulator that has fewer non-target impacts than the broad spectrum organophosphate insecticides also registered for this pest (Ferguson et al. 1996; Young 2019).

There are, however, major pests where only a small subset of these control options are available. For example, black beetle (*Heteronychus arator*) is an introduced pest that has few associated pathogens (Bell et al. 2011). Only two neonicotinoid insecticides are registered for seed treatment to protect pastures at sowing, but no insecticides are registered for its control in established pasture (Young 2019). With this pest, ryegrass cultivars infected with endophytes that deter black beetle adults are the primary management tactic, although their effect on black beetle varies among cultivars, e.g. AR1 is ineffective whereas AR37 and NEA2 are highly effective (Bell et al. 2011; Thom et al. 2014). However, even the most effective endophyte-infected cultivars do not make pastures completely resistant to black beetle. Their presence in the pasture will reduce oviposition, but when alternative host plants without endophytes, such as poa or summer grasses, are also present, damaging black beetle populations can still develop (Bell et al. 2011).

In addition to endophyte-infected ryegrass cultivars, some alternative pasture species and hybrids are either tolerant of or resistant to insect damage. For example, endophyte-infected meadow fescue has resistance to

Table 1 IPM components present in pastoral systems in New Zealand. These components consist of the IPM toolkit (control measures used against pests) and the IPM framework that helps farmers to make decisions about pest management (monitoring, thresholds, decision support and information).

IPM toolkit	Availability	Supporting information
Chemical control	Organophosphate insecticides are the predominant products registered for control of pasture insects. An insect growth regulator is available for porina. Neonicotinoid seed treatments may be used at sowing to protect seedlings. Some pests, including black beetle, have no registered insecticides for established pastures.	Latest edition of New Zealand's agrichemical manual, Young 2019
Cultural control	Stock treading or heavy rolling may be used to crush pasture insect pests. Direct drilling is preferable to cultivation for pasture renewal, to minimise loss of co-evolved pathogens.	Stewart et al. 1988; Jackson 1990; Atkinson & Slay 1994
Plant resistance	Endophyte-infected ryegrass cultivars contribute substantially to control of black beetle, Argentine stem weevil, porina, etc. Some alternative pasture species are more tolerant of pest damage, due to either endophytes or other mechanisms.	Popay et al. 2003, 2005 and 2012; Thom et al. 2014; Barker et al. 2015
Biological control	Introduced parasitoids target Argentine stem weevil, clover root weevil and lucerne weevil. Co-evolved pathogens contribute to suppression of endemic pests: grass grub, porina, manuka beetle.	Fleming et al. 1982; Jackson 1990; Goldson et al. 2005; Townsend et al. 2010
IPM framework		
Economic thresholds	Established for major pests and some minor pests. Thresholds differ between sectors, reflecting value of animal production.	Ferguson et al. 2019 and references therein
Monitoring	Sampling methods and protocols available for major pests but very labour intensive.	Zydenbos et al. 2013; Ferguson et al. 2019
Decision support tools	Flow charts available to assist decisions for grass grub, manuka beetle, porina.	Zydenbos et al. 2013
Information sources	AgPest™ website for insect pests and weeds is free for all users. Offers a text or email alert service by subscription. Field days, discussion groups, fact sheets and other web-based resources are available through sector levy bodies.	AgResearch 2019; Beef + Lamb New Zealand 2019b; DairyNZ 2019b

grass grub (*Costelytra giveni*; formerly *C. zealandica*) (Popay et al. 2003). New Zealand pastures, however, are dominated by ryegrass (with or without endophytes) and ryegrass is the most valuable plant for New Zealand, with red and white clover (*Trifolium* spp.) as the third most valuable type of plant nationally after radiata pine (*Pinus radiata*) (Nixon 2016). Of the alternative pasture species available, chicory (*Cichorium intybus*) was ranked 20th with all other species ranked even lower (Nixon 2016). It is unclear how much influence insect pest management has on the selection of pasture species by farmers, but these rankings indicate that ryegrass and clover are the dominant pasture plants, with only limited uptake of alternatives.

Current monitoring and thresholds

Key to an effective IPM program is the ability to monitor pest numbers in order to detect situations where pest populations threaten to exceed economic thresholds. The lack of effective monitoring methods was an early, but significant, barrier to IPM adoption in New Zealand apple orchards (Walker et al. 2017).

In the New Zealand pastoral system, farmers can monitor pest numbers and use simple damage thresholds to determine if control measures are needed for outbreaks of grass grub, manuka beetle (*Pyronota* spp.) or porina (Jackson et al. 2012; Zydenbos et al. 2013). More recently, Ferguson et al. (2019) developed economic thresholds for these and other significant pests for dairy or beef/sheep pastures. There are some pests, however, that do not have economic thresholds established, although their impact on pasture is recognised (e.g. pasture mealybug *Balanococcus poae*; Pennell et al. 2005).

Where economic thresholds are known, monitoring of pest numbers remains a substantial problem in pastures because the main method of monitoring pests involves digging and sorting approximately 15 spade squares/paddock, which is too labour intensive for farmers to implement effectively. Often this means farmers are not alerted to the presence of damaging pest populations until their impact on the pasture is easily visible. By this time, production losses have already occurred and long-term reductions in pasture quality may be irreversible, contributing to poor pasture persistence (Zydenbos et al. 2011).

Existing decision support and extension

Levy bodies associated with the pastoral sector provide information about pest management to their members and invest in extension officers who engage with farmers about all aspects of farm management, including pests (Table 1). These information sources are also important for product processing groups, such as Fonterra or Silver Fern Farms, and agribusiness representatives from companies that supply farmers with seeds, fertiliser, insecticides, etc, because representatives from these businesses engage frequently with farmers.

Decision tools, in the form of flow charts or tables, exist for grass grub, porina and manuka beetle to assist farmers to assess if pest numbers are at damaging levels and then determine which control measures, if any, are warranted (Zydenbos et al. 2013). Each of these tools is focused on a single pest, yet it is common for more than one pest species to occur in a single paddock (Zydenbos et al. 2011). Ideally, farmers should be able to evaluate the combined impact of the pest complex present in their paddocks before making decisions about pest control measures, but the pest-specific information available has yet to be synthesised to support this. Developing a comprehensive decision support system is difficult because pasture supports dairy, meat and wool production, as well as smaller industries, such as deer, yet pasture insect pests occur across industry boundaries. Consequently, there is no comprehensive pasture IPM programme that encompasses all insect pest species for all pastoral industries. This situation reflects the presence of significant practical barriers to more widespread adoption of IPM by pastoral farmers.

Barriers to IPM adoption by pastoral farmers

Pastoral farming poses two significant challenges to scientists who want to develop IPM strategies and to farmers who want to adopt IPM practices. The first challenge is that, unlike cotton, pasture is not the primary product. It supports dairy, meat and wool production, each with their own value chains and different expectations for economic returns. The expected economic return from a pasture affects all IPM decisions, from the economic threshold for each pest to the cost-benefit ratio for each control option. This is demonstrated clearly by Ferguson et al. (2019), who compared the cost/ha of several significant pasture insect pests for dairy versus sheep/beef production.

The second challenge is that pastoral farming takes place across a wider range of environments (terrain, soil type, geographic, climatic) than any other primary sector in New Zealand, representing 40% of our total land area (Morrison 2017; Ministry for the Environment & Stats NZ 2019). This challenge is similar to that for the Australian cotton industry which extends across a 15° latitudinal range from the tropics to the temperate regions. Because of this range, the cotton industry has different economic pest thresholds and resistance management requirements in different regions (Wilson et al. 2018; Sequeira et al. 2018). An IPM programme for New Zealand's pastures must have the flexibility to accommodate the diversity of pastoral farm systems.

Existing IPM toolkit limitations

The pest control toolkit currently used in New Zealand pastures needs to expand to support IPM adoption. At present, organophosphate insecticides, which are harmful to pests and beneficial species alike, are used frequently because few, if any, alternatives are available. In cotton, the move to more selective insecticides was a major breakthrough as it enabled beneficial species, such as predators and parasitoids, to flourish in the crop and assist with pest control (Wilson et al. 2018). Using broad-spectrum insecticides disrupts biological control of both target pests (e.g. natural pathogens of grass grub, Jackson 1990; Zydenbos et al. 2016) and non-target pests (e.g. introduced parasitoid of clover root weevil, *Sitona lepidus*; McNeil et al. 2014). Ryegrass cultivars infected with insecticidal endophytes are the other key control measure, at least for above-ground pasture insect pests. The use of such cultivars is more compatible with biological control than the use of chemical insecticides on uninfected cultivars (Popay et al. 2011). However, there is some evidence for detrimental interactions between fungal endophytes and parasitoids (Goldson et al. 2000; Urrutia et al. 2007). New control methods need to be compatible with other sustainable, environmentally benign control strategies (pre-existing or new), particularly biological control and pest-resistant pasture species or cultivars, and compatible with the whole farm system, if they are to support IPM adoption.

Lack of monitoring and thresholds

A first step to develop a comprehensive IPM programme for pasture will be to establish sector and/or region-specific thresholds for all insect pests that have the potential to cause pasture damage. Thresholds are a key aspect of IPM in cotton that are continually updated and refined for a range of pests (e.g. Sequeira et al. 2018). It is preferable that in pasture these thresholds, usually expressed as pest numbers/m^2, are related to a consistent method of evaluating pasture damage, so that it is easy to quantify monetary losses associated with each pest and, perhaps more importantly, the losses from multiple pest species in the same pasture. Historically, the relationship between pest numbers and pasture damage has been expressed in different ways, e.g. decline in dry matter production/ha (Blank et al. 1985), percentage loss of pasture cover (Hardwick et al. 2000), percentage of ground cover (Pennell et al. 2005), or changes in pasture composition (Zydenbos et al. 2016). A more consistent approach to measuring pest pressure would enable stakeholders to compare pasture damage caused by different pest species across farm systems (as demonstrated by Ferguson et al. 2019 for dairy versus beef/sheep). It would also enable farmers to compare the efficacy of different control measures and evaluate the cost-benefit analyses for new IPM tools.

Development and validation of new monitoring methods to replace or complement the time-consuming evaluation of soil squares is essential for timely application of control measures and may pave the way to more comprehensive decision support tools that address management of multiple pests, rather than the single species tools available to farmers now (Zydenbos et al. 2013).

Limited decision support and extension

Support and extension are key to a successful IPM programme. In cotton, a unifying challenge to its existence galvanised the Australian cotton industry to respond with co-ordinated support and extension programmes. In this respect, IPM of pasture faces major challenges because it is managed by several different industries with different levels of profitability and cultures, which makes it difficult to co-ordinate decision support.

In addition, farmer perceptions regarding the profitability of new technologies and how easily they can test new control options on their own farms are important factors driving adoption (Cullen et al. 2008). Pasture insect pests are difficult to observe because they either live underground or those that live above ground are small and well concealed within the pasture canopy. The concealed habits of pasture pests, combined with labour-intensive monitoring methods, make it difficult for farmers to assess the efficacy of new control options. Assessment of profitability is also challenging because it is based not only on measurable improvements in pasture growth but the timing of that improved growth relative to demand for livestock feed and seasonal cycles (Morrison 2017). Investment in training, decision support, knowledge extension and technology transfer is essential for farmers to have confidence in IPM as a new approach to pest management and to ensure that the IPM toolkit fits within the wider farm system. Industry bodies and research providers already engage in this aspect of IPM (Table 1) but greater investment will be needed to support the transition from reactive responses following visible pasture damage to pre-emptive responses that prevent pasture damage.

Potential solutions to increase IPM adoption

Potential solutions that are expected to increase adoption of IPM by pastoral farmers include new monitoring methods for pasture insect pests, new control measures to replace harmful insecticides, and new approaches to extension.

An expanded IPM toolkit

The aim is to replace harmful broad-spectrum insecticides with biopesticides that are effective and environmentally benign. Extensive research has occurred over many years into the development of biopesticides that target endemic pasture insect pests, particularly grass grub. However, this is the only pasture insect to date that can be controlled using a registered biopesticide (Jackson et al. 1992; Zydenbos et al. 2016; Wright et al. 2017; Young 2019). Suitable candidates for new biopesticides have been identified (Hurst et al. 2014; Hurst et al. 2018), and a prototype biopesticide has been tested in pastures against porina and black beetle (Mansfield et al. 2016; Hurst et al. 2019), but commercialisation of biopesticides for New Zealand's small market has proven challenging. Development of any new active ingredient, whether for a chemical or a biological pesticide, faces substantial regulatory hurdles to achieve registration in New Zealand, such as demonstrating efficacy and safety in New Zealand's unique environment (summarised for biopesticides by Glare & O'Callaghan 2019). There are also industrial capacity constraints that limit local manufacture of biopesticides in large volumes (Glare & O'Callaghan 2019). Cross-sector collaboration to leverage capital investment into new pest control products, particularly for pests that are specific to New Zealand, is likely to be required to meet the necessary registration requirements for new active ingredients and increase local production capacity. Without such investment, withdrawal of organophosphate insecticides and probable future restrictions on neonicotinoid use (Hladik et al. 2018; Hall & Steiner 2019) will leave a substantial gap in the suite of pest-control strategies available to pastoral farmers. Weed control in pastoral agriculture faces similar challenges, after suggestions to withdraw glyphosate from the EU (Székács & Darvas 2018), an important tool for New Zealand pastoral farmers.

Improved monitoring and thresholds

Recent research into new monitoring methods has demonstrated a detectable change in pasture characteristics that signals the presence of grass grub (Zydenbos et al. 2019). These patches of grass grub were then targeted with a biopesticide. If the presence of damaging pest populations can be detected remotely through changes in the pasture, farmers will be able to gather spatially explicit data about pasture insect pests that can be placed alongside other spatial data, such as nutrient status, soil type and moisture levels. Many farmers already gather such data to make decisions using farm management tools (e.g. Farmax; Bryant et al. 2010). The ability to integrate pest data into existing decision tools will encourage pro-active pest management. Such possibilities are, however, at a very early stage of development for the pastoral sector with most investment focused on remote monitoring of pasture quality using novel imaging techniques (e.g. Pullanagari et al. 2018). The potential to extend remote imaging techniques from monitoring plant health to detection of insect pests exists in forestry (e.g. Abdel-Rahman et al. 2014; Lehmann et al. 2015), but this has not yet been demonstrated for pasture. Significant investment in research, validation, and co-development to ensure compatibility with existing farm systems is needed to take new approaches to monitoring beyond proof-of-concept to real world adoption by the pastoral sector.

Development of economic thresholds and new monitoring tools, as discussed above, will demonstrate the value proposition for IPM adoption by pastoral farmers. Industry-support people, such as DairyNZ consulting officers, farm advisors and consultants, need to be trained in IPM so that they are confident in sharing their IPM knowledge with farmers. Across all areas of extension, information about IPM needs to be consistent, accurate, and tailored to farmers' requirements. Adoption of IPM will be more complex for pastoral farming due to its inherent diversity – an IPM programme for a Waikato dairy farmer will differ from that for a Southland sheep and beef farmer, just as a cotton farmer in southern New South Wales has a different IPM programme to one in tropical Queensland (e.g. different thresholds for mirids, Whitehouse et al. 2011; Sequeira et al. 2018). This complexity should not be a reason for apprehension because pastoral farmers already manage this diversity in their current farm systems. In future, farmers may employ trained technicians or consultants to gather the data necessary for IPM. This is common among New Zealand apple growers (Walker et al. 2017) as well as Australian cotton farmers (Wilson et al. 2018), and is similar to current practice by Pāmu, who use technicians to monitor pasture growth. This practice contributed to development of the manuka beetle decision tool when outbreaks of manuka beetle caused significant damage on Pāmu land at Cape Foulwind (Jackson et al. 2012; Zydenbos et al. 2013).

Expanded decision support and extension

Adoption of IPM by pastoral farmers needs more than technological solutions: it requires a change in human behaviour. Achieving equivalent shifts in other crop systems has taken years of investment to support effective communication between researchers, farmers, and other industry stakeholders (levy bodies, contractors, consultants, etc.) and social research to ensure new IPM programmes fit within the wider crop system (Walker et al. 2017; Wilson et al. 2018). Verbal communication should be prioritised with written and/or online support, such as AgPest™ (Tozer et al. 2017), acting to reinforce key messages along with tools for pest identification and decision support. Demonstration farms that are owned or managed by farmer champions of IPM are a recognised strategy for encouraging IPM adoption in New Zealand's arable sector (Horrocks et al. 2010; 2018); a strategy that could be used by the pastoral sector as new IPM tools enter the market. Field days, discussion groups, seminars and other web-based resources that are supported through pastoral industry levy bodies are another key contact point for sharing new ideas about IPM (Table 1, Wilson et al. 2018; DairyNZ 2019a; Beef + Lamb 2019a). Adoption of IPM adds a new dimension that will improve the sustainability of pastoral farming.

Closing remarks

The pastoral industry faces a major challenge from the loss of important insecticides, with the organophosphate diazinon scheduled for deregistration in 2028. Concurrently, the pastoral industry faces significant public concern about its environmental footprint, due to nutrient leaching into waterways and greenhouse gas emissions (Ministry for the Environment & Stats NZ 2019). Developing a comprehensive IPM system in New Zealand pastures would counter the loss of organophosphates and enhance the pastoral industry's social licence by developing a more sustainable insect pest control regime that reduces the frequency of pasture renewal and the need to repair pastures damaged by insect pests.

Currently, IPM within New Zealand's pastoral sector could be described as cryptic: farmers use more than one strategy to control insect pests and economic thresholds are established for the most significant insect pests, but the system is not universal or well supported. For example, control measures are often applied too late to prevent damage or to recover from damage already incurred.

The first priority in creating an effective IPM system is to develop efficient monitoring tools for insect pests so that farmers can apply control measures before economic thresholds are breached. The second priority is to expand the current IPM toolkit with new control options to replace broad-spectrum insecticides. The third priority is to develop decision support that encompasses the full range of insect pests that occur in pastures. Addressing these priorities will overcome important barriers to IPM adoption for pastoral farmers. Novel control strategies and digital technologies to monitor pests have strong potential to address these priorities and improve pasture IPM, but greater investment is needed to develop these new control strategies and digital technologies so that they are available to farmers, and to encourage farmers to feel a sense of ownership for IPM. An IPM programme for New Zealand's pastoral farmers needs to address all pests and offer a suite of compatible control strategies that can be tailored to the needs of individual farms.

Finally, an IPM programme for New Zealand's pastoral farmers needs to be a united effort. Combined support from all the industries that depend on pasture is necessary for the social support farmers need to implement an IPM approach. Recognising that there is a need for change, and an advantage to adopting an IPM approach is the first step.

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