Implications of insecticide resistance for the control of flystrike and lice on sheep.

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Summary

The Australian sheep blowfly (Lucilia cuprina) and the sheep body louse (Bovicola ovis) have both demonstrated their propensity to develop resistance to insecticides used for their control. Most populations of L. cuprina contain individuals resistant to organochlorines and organophosphates. Some are also resistant to benzoylphenyl ureas. Many populations of B. ovis are resistant to pyrethroid insecticides. However, very few populations are resistant to organophosphates. Treatments directed at lice infestations have selected for resistance in sheep blowfly so insecticide treatments need to be considerate of the possible impact on non-target parasite resistance. Flock management plans would assist in identifying options for producers but clearer information on pesticide residue/environmental requirements are needed first.

Organophosphate resistance in sheep blowfly is almost universal. These insecticides are of limited use against this pest even as flystrike dressings. Organophosphates can still be effective lousicides but application (plunge or shower dipping) to short wool sheep is extremely difficult and often fails to eradicate an infestation. Further work is needed to improve wet dipping and simplify maintenance of dip concentration. The future of these products is unknown as they are subject to regulatory review on environmental and safety grounds but currently they are very valuable to the wool industry.

There are still effective products available for sheep blowfly and lice control. Flystrike prevention is heavily reliant on cyromazine and lice control reliant on triflumuron and diazinon. Spinosad is a long wool option, should follow up or late season treatments for either parasite be needed. Resistance to any of these compounds would seriously jeopardise producers' ability to control flystrike and lice infestations. Consequently, field surveys and cross resistance studies to determine baseline population responses to potentially new compounds remain necessary to responsible pest control decision making.

Keywords

Insecticide resistance, *Lucilia cuprina*, *Bovicola ovis*

Introduction

Control of sheep ectoparasites is currently an integration of sheep husbandry, farm management and insecticide use. Insecticides have served the wool industry well and their cost effectiveness has never been questioned. They have, perhaps, been too successful leading some producers to over rely on insecticide treatments. The result of widespread chemical use has been the sequential development of resistance to three insecticide classes in sheep blowfly, *Lucilia cuprina* and at least one in sheep body lice, *Bovicola ovis*. *L. cuprina* breeds almost exclusively on live sheep and lice do not survive away from their host so the only true refugia from insecticide resistance selection pressure is untreated sheep. Unfortunately, but not surprisingly, the development of insecticide resistance, particularly in sheep blowfly, followed only a few years behind the release and broad scale use of the various insecticide groups.

Resistance and sheep blowfly insecticidal control

BHC and DDT were used for flystrike and lice control from 1948 until 1954 when they were replaced by the more efficacious cyclodienes aldrin and dieldrin. No resistance to dieldrin was detected in sheep blowfly populations in 1954 but by 1958 70% of flies were resistant (Hughes and McKenzie, 1987). In the absence of further selection pressure the frequency of dieldrin resistance has dropped to 2-3% (Levot, 1995a).

The OCs were replaced by the organophosphates (OPs) in 1958 when unacceptable meat residues led to their withdrawal. By this time field failures were becoming more common. Of the registered OPs diazinon, chlorfenvinphos, coumaphos, fenthionethyl and carbophenothion were the most popular. The latter two were deregistered in 1988. Propetamphos became available for use on sheep in 1986. Field failures were common from the time the OPs were first registered. Unlike dieldrin and aldrin, the OPs needed to be applied thoroughly as they did not move laterally from the application zone. This made the diagnosis of resistance difficult as many producers had problems with the new products from the beginning. Routine monitoring of blowfly populations detected low-level resistance in about 20% of adult blowflies in 1965 (Shanahan and Hart, 1966) about 8 years after their first release. By 1970, about 95% of flies were diazinon resistant. Resistance has now stabilised at 97-98% (Levot, 1995a). At the practical level OP resistance reduced the flystrike protection provided by OPs from 16 weeks to around 4 weeks. Diazinon residues in wool following hand jetting of sheep remain high (approx. 50 mg/kg) for at least 120 days after treatment and yet flystrike protection lasts for only about 30 days (Levot and Sales, 1997). There can be little justification for using OPs for this purpose but OPs remain the cheapest effective treatments for lice control.

Between 1965 and 1979 there were no alternatives to OPs so farmers could only change from one OP to another. Although resistance to OPs is almost universal in Australian sheep blowfly populations, resistance levels (Resistance Factors) vary between 2 and 60. This impacts, not only on the effectiveness of OP products but on those containing diflubenzuron as well (see below). OPs still represent the major chemical group used to dress active strike lesions. Levot *et al.* (1999) clearly demonstrated reduced effectiveness of most OP flystrike dressings against a composite field strain of *L. cuprina* that was 33 times resistant to diazinon. Aqueous diazinon based products generally killed about 50% of larvae irrespective of treatment exposure time but only about 14% mortality was recorded for larvae exposed to an aqueous chlorfenvinphos-based treatment. Few registered products performed adequately. As well as having relevance to the treatment of flyblown sheep, these results have implications for woolgrowers that jet struck sheep with OPs, or mixtures of cyromazine and an OP. The results indicate that the OPs are not capable of killing all larvae. For this reason NSW Agriculture no longer recommends mixing OPs and cyromazine to jet struck sheep.

With OPs generally being incapable of killing larvae in strikes the main purpose of OP flystrike dressings becomes protection of treated strike wounds from restrike. Results of a field trial of many of the registered products demonstrated that most, when combined with shearing, protected sheep at least for a period long enough to allow wounds to heal (Levot and Sales, 1998).

Whereas dieldrin resistance developed within three years of its introduction, resistance to the OPs took about 8 years to evolve. This raised speculation as to why such a difference in the rate of evolution should have occurred given the methods and extent of treatment used by woolgrowers had not changed appreciably during that time. Research by John McKenzie and Max Whitten explained the dilemma by demonstrating the influence of pre-selection with lindane louse treatments and in terms of the relative fitness of the various blowfly genotypes. The rate at which resistance develops is determined during the period when heterozygotes (R/+) become established in a previously susceptible (+/+) population (Whitten and McKenzie, 1982) and relates to the relative advantage heterozygotes have over susceptible individuals. They may be explained as a rate, with selection for resistance occurring when the ratio of the fitness of the +/+ is less that that for R/+. The relative fitness of +/+ and R/+ were measured on sheep jetted with diazinon or dieldrin (McKenzie and Whitten, 1982; McKenzie and Whitten, 1984). Selection for diazinon resistance extended well beyond the period that sheep were considered 'protected' from flystrike. McKenzie and Whitten (1984) also demonstrated that the fitness of dieldrin heterozygotes was significantly greater on lindane treated sheep. Lindane (BHC) had been used for 6 years prior to the introduction of dieldrin. It seems likely that the dieldrin resistance gene was selected during the pre-dieldrin period when lindane was commonly used. Therefore, resistance had taken 9 years, not 3, to develop - a remarkably similar period to that for OP resistance development.

The triazine pesticide cyromazine was registered for flystrike prevention in 1979. Organophosphate resistant flies were equally susceptible to cyromazine (Shanahan and Hughes, 1980) so farmers, at last, had a product capable of provided long-term (14+ weeks) flystrike protection. Cyromazine is a slow-acting insect development inhibitor that is less suitable for dressing strikes. Unlike the other insecticide classes, activity does not extend to sheep lice. Based on the experience with resistance to the OCs and OPs it was reasonable to expect that resistance to cyromazine could have developed before 1990. However, despite 20+ years of extensive use throughout all sheep raising areas of Australia cyromazine continues to perform well with no resistance reported. Occasional field failures occur but these can usually be traced to poor jetting technique or heavy rain soon after treatment. Nevertheless, several producers have reported that they believe cyromazine does not provide the length of protection that it once did under similar conditions. Several generic cyromazine products are now available, both as jetting and spray-on formulations. In 1998 dicyclanil, a compound closely related to cyromazine, was released as a spray-on flystrike preventative. It is about 10 times more potent than cyromazine in laboratory bioassays and carries a claim for 26 weeks flystrike protection.

An unrelated class of insect growth regulators is the benzoylphenyl ureas. In this class diflubenzuron and triflumuron have been formulated for use on sheep in Australia. Triflumuron is only registered for sheep lice control at present but diflubenzuron is available for use against both lice and blowflies. Both compounds have been widely used and are known to be quite persistent in the fleece. We have surveyed sheep blowfly population responses to diflubenzuron for many years and found them to range about 30 fold at LC50. Most population responses were clustered 'normally' around the reference 'susceptible' strain's response, however, a handful of populations were found to be resistant. In a survey of over 75 field populations, toxicological responses to diflubenzuron were significantly correlated to those to diazinon (Sales *et al.*, 2001). Maximum Resistance Factor to diflubenzuron was 24 whereas maximum diazinon RF was about 60. This is a true cross resistance problem, as many of the field populations tested had not been exposed to diflubenzuron. The four highest diflubenzuron responses measured were for populations that had survived on diflubenzuron treated sheep and had been the subject of producer complaints. To investigate this further, we conducted a larval implant trial with diflubenzuron resistant and susceptible larvae on diflubenzuron treated sheep. We found that the resistant types established strikes significantly earlier than susceptible larvae (Sales *et al.*, 2001). Moreover, we have pressured a population of sheep blowfly derived from the field with diflubenzuron such that it is now routinely cultured on homogenised liver containing 50 mg diflubenzuron/kg whereas 5 mg/kg would be lethal to susceptible populations.

Pyrethroid insecticides are relatively poor larvacides against *L. cuprina* but several were registered as oviposition suppressants. A few pyrethroids had already been in widespread use as sheep lousicides. As with diflubenzuron, high resistance in larvae could be selected in the laboratory but oviposition suppression was unaffected (Sales *et al.*, 1996).

Spinosad was registered this year for sheep blowfly and lice control. We measured the responses of 41 field populations of *L. cuprina* to spinosad. Responses were similar to the reference susceptible strain. This compound has only short residual activity. This characteristic is likely to reduce the likelihood of resistance developing. Its non-persistence in the fleece has allowed it to carry a nil withholding period for meat and wool.

Resistance and sheep lice control

Agrochemical companies see a marketing advantage in having products registered against both blowfly strike and lice infestations. The history of insecticide resistance development in sheep blowfly, however, implicates lice treatments with the same or related compounds as being responsible for initial, or concurrent resistance selection. It is clear lice control treatments have impacted on producers' ability to protect sheep adequately from blowfly strike. Control strategies for the two pests should be considered jointly, not in isolation so that insecticide resistance selection is minimised or at least considerate of control of the other pest.

After the deregistration of the OCs and until the registration of pyrethroid lousicides, producers used arsenic-based products and OPs for lice control. During this time the incidence of properties with lice was 25-30% nationally, despite the regulatory threat of quarantining of lousy flocks. Products were applied via plunge or shower dipping but clearly, many treatments were ineffective. Other papers at this conference provide some insight as to why this was, and indeed still is, the case. In 1981 pyrethroid pour-ons were registered and achieved 70% market share within a few years. There were several advantages: chemical could be applied directly after shearing, thereby avoiding the need for a second muster; treated sheep were readily identifiable by the scourable dye mark left on their backs; no water was required, there was no need to handle or mix insecticide as the products were sold ready for use; it was not labour intensive; the only specialised equipment required was the appropriate applicator; there was no unused 'spent' chemical to discard; and, the whole process is readily transportable. Unfortunately, by mid 1985 reports of failures of the pour on pyrethroid products were becoming increasingly more frequent.

Among the causes of control failure was the possibility that lice had become pyrethroid resistant. A laboratory bioassay was developed and used to describe the toxicological responses to cypermethrin of about 30 lice populations, mainly from properties experiencing problems in controlling lice (Levot and Hughes, 1990). The frequency distribution of responses fitted a broad normal distribution. Maximum resistance, compared to the most susceptible strain was 19 fold. Later, when almost 50 louse strains had been tested, the maximum resistance in this 'normal' group of populations was 26 (Levot *et al.*, 1995). Johnson *et al.* (1992) working with the same louse strains reported that this level of resistance was sufficient to reduce the effectiveness of some of the off shears pour-on products but no strain survived the commercial dose wet dip rate of 19 mg cypermethrin/L. About that time a strain of lice from Hartley NSW was found to be 642x resistant to cypermethrin (Levot, 1992) and able to survive both pour on and full immersion aqueous cypermethrin dips (Levot, 1995b). Since then, several other high resistance strains have been reported from NSW, South Australia (James *et al.*, 1993) and Victoria (Keys *et al.*, 1993; Martin, 1993). Correlation analysis of the toxicological responses measured in the bioassays proved that resistance to one pyrethroid conferred resistance to the others (Levot *et al.*, 1995b).

Pyrethroid resistance was found to be suppressible by co-treatment with monooxygenase inhibitor piperonyl butoxide (Levot, 1994a) with synergism ratios of about 20 recorded. In an effort to overcome resistance in the field a small-scale trial was conducted with a novel cypermethrin/piperonyl butoxide (1:5) formulation containing 19 mg cypermethrin/L and with similar formulations containing no cypermethrin or no piperonyl butoxide. Throughout the 10 weeks trial period significantly better lice control was achieved with the mixture than with cypermethrin alone. Whereas lice burdens on the cypermethrin treated sheep had returned to pre-treatment levels within 10 weeks, there was still an 81% reduction in lice numbers on the sheep treated with the mixture (Levot, 1995b).

At present, there are no known pyrethroid resistant lice populations that are not susceptible to OPs. A resistance monitoring survey of NSW flocks identified only one population whose response to diazinon was significantly removed from the normal range of responses (Levot, 1994b). This population had survived several on-farm diazinon treatments but eventually succumbed to extremely thorough dipping in diazinon. Ironically, this strain was extremely susceptible to pyrethroids and could have been eradicated using a pyrethroid pour on product.

Toxicological responses to diazinon and cypermethrin were completely independent in all populations (Levot, 1994b). In fact, conversely to the diazinon resistant strain, the pyrethroid resistant Hartley strain was one of the most diazinon susceptible strains tested. OPs offer the cheapest option for the control of pyrethroid resistant sheep lice. Moreover, should resistance to insect growth regulators such as diflubenzuron and triflumuron develop, producers may have to rely on OPs again. In this respect alone, OPs are vitally important to wool producers.

Diflubenzuron and triflumuron are registered for lice control. Triflumuron is currently only available as a low volume pour on for short wool use but has gained a very large market share. Generally performance is rated very highly and producers have accepted the slow kill that is a feature of these insect growth regulators. Diflubenzuron was registered as a wet dip some years ago but has recently been marketed as a pour-on as well. As with all products there have been some complaints regarding performance of the benzoylphenyl ureas but generally producers have been pleased with the results. Unlike the OPs or pyrethroid insecticides there is no rapid *in-vitro* test to detect resistance to insect growth regulator insecticides. Instead controlled pen trials are required. These must be run for sufficient time for the products to have their effect. There are no reports of confirmed resistance in *B. ovis* to these insecticides although there are a number of field failures.

Spinosad is registered for lice control in long wool. Spinosad was equally effective against susceptible and highly pyrethroid resistant sheep body lice in laboratory bioassays. Compared to data for some registered compounds, spinosad had toxicity against *B. ovis* similar to diazinon and other organophosphates. Toxicity to susceptible lice was less than the registered pyrethroids however, at the LC50 level, spinosad was more than 10 times more effective than cypermethrin against a pyrethroid resistant strain.

Field failures

Resistance and poor initial pesticide application are the two most common reasons for repeat insecticide treatment of sheep. It is not unusual for mobs to have been treated 2, 3 or even more times with a product before a thorough investigation of the cause(s) of control failure is conducted. Failure to eradicate lice with off-shears or short wool treatments may not be evident until 6-10 months later. With IGRs it may be difficult to detect lice even at the next shearing.

Dicyclanil can be applied to prevent flystrike in excess of 20 weeks before the anticipated flystrike period but most products provide protection for 12-14 weeks. These intervals allow most producers to manipulate treatment date to provide adequate flystrike protection and also satisfy withholding periods. A breakdown during the period when sheep should still be protected, however, will necessitate a second treatment that may compromise withholding periods, rehandling intervals, residues and add significant financial costs.

Resistance management

Resistance management relies on the preservation of insecticide susceptibility. One of the best ways of maintaining susceptibility is to rotate the use of different chemical classes (Sawicki, 1981) but avoiding the use of insecticides altogether is the ultimate strategy. An inability to use anything other than OPs in the late 1960s and 1970s drove OP resistance to near fixation levels and gave *L. cuprina* time to overcome the initial fitness disadvantage associated with resistance. As well, failure to use unrelated compounds for lice and blowfly control accelerated the development of dieldrin resistance in *L. cuprina*.

Presently, in terms of resistance management woolgrowers are in a good situation. Cyromazine is still extremely effective against sheep blowfly and dicyclanil provides extraordinary length of protection. OPs, if used correctly are excellent lousicides. Pyrethroid dips are still effective against most louse populations even if pour-ons are less reliable. Triflumuron and diflubenzuron pour-on lousicides appear to be performing well even if cross resistance to diflubenzuron in highly OP resistant blowflies is a problem. At present, spinosad is the 'fall back' for control failure. With its nil withholding period it can be used right up to shearing. Of course, over reliance on this product will put extra pressure on it as well. There are no alternatives with similarly favourable characteristics.

Both sheep blowfly and sheep body lice have demonstrated their propensity to evolve resistance. For the long-term preservation of treatment options improvements are needed to make louse treatments almost foolproof. To achieve this wet dipping needs to be simplified. To date, producers who have had failures with pour-on type louse treatments have been directed to resume wet dipping, usually with an OP. It is quite likely that the producers who are experiencing problems had changed to pour-ons because they had not been able to eradicate lice by wet dipping with OPs. The irony here is that they are being encouraged to return to a practice that has already failed. Non-insecticidal control strategies need to be better exploited and clearer messages regarding market requirements for residues and environmental constraints for pesticide use are required as a matter of urgency.

Future priorities for sustainable insecticide resistance management

Pest management calendars/diaries that provide producers with options for responsible control strategies for flystrike and lice are needed. Unfortunately, it seems these must be tailored for individuals as many woolgrowers see their situation as unique. Too often producers will say that products to suit their management are needed rather than them changing their management to suit the available insecticide technology. In developing management plans all the variables impacting on the utility of the various insecticide product classes need to be clearly understood. These include; wool withholding period(s), stock rehandling interval, export slaughter intervals for all products being considered; any existing resistance complications; other farm enterprises eg. cropping; whether there is a need to treat for lice and blowfly; shearing time(s); lambing time; joining time; worst flystrike period, flystrike protection period needed/provided; etc. Sometimes these farm plans can identify a fundamental constraint within the current management plan that precludes adoption of a preferable pest control practice. In these cases a total rethink of fundamental farm timetabling, including shearing date, is required.

At the insecticide level there is a continuing need to monitor field populations for their susceptibility to the insecticides upon which current pest control and residue management strategies rely - particularly, cyromazine. New compounds should be tested against standard resistant strains to highlight likely cross-resistance problems. They should also be tested against a large number of field populations so that baseline data can be collected. Future resistance diagnosis relies on comparison with this baseline data.

Lice control is heavily reliant on triflumuron with the related diflubenzuron seeking to gain a larger market share. Resistance to these insecticides will again force woolgrowers back to OP products. These are difficult to use due to overly complicated label instructions. Co-operation from agri-chemical companies and the National Registration Authority is required to assist re-labelling. Further work is required to simplify wet dipping if OPs are to remain an option. OPs, however, are under increasing threat of being lost due to environmental and OH&S concerns. To maintain these relatively cheap products for woolgrowers more information on the responsible use and disposal of OP dip solutions are required to satisfy regulatory and social requirements.

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