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Modelling pesticide residues on greasy wool: using organophosphate and synthetic pyrethroid survey data

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Summary. Several surveys have examined the relationship between organophosphate and synthetic pyrethroid residues in wool and associated treatments. These have been combined and summarised using a model of on-farm survey data. The model estimated the amount of chemical taken up by the wool at application. This was based on experimental breakdown rates of these pesticides on wool determined in controlled trials.

For about 10% of survey results the chemical measured on the wool did not match the chemical the producer said was applied. A further 5% of results were excluded because the amount of chemical detected on the wool was inconsistent with the stated time of treatment and shearing. With the remaining results there was a very high variation in residues resulting from the same (stated) treatment. It is clear that many producers do not know what chemicals they have used or how much they applied. The wide variation in results suggests that some producers may apply excessive amounts of pesticides while others use too little to have a useful effect.

The model estimated the amount of pesticide taken up by the fleece using the residue left at shearing and the known breakdown rate for a given method and chemical group. When organophosphates were applied by dipping, the amount of chemical taken up by the fleece appeared to increase as the length of the wool increased. This was generally higher than would be anticipated from label dose rates but was consistent with the stripping characteristics of these chemicals. Therefore dipping as soon as possible after shearing left much lower residues (<10 mg/kg wool) than delayed treatment (often 10–30 mg/kg wool). In contrast the survey results suggest that the amount retained by sheep as a result of jetting decreased in longer wool. Jetting treatment rates appear to be lower than recommended, particularly for sheep with more than 6 months wool. Therefore jetting (as used by producers) left much lower residues in wool than dipping (with similar length wool) and was usually only above 10 mg/kg wool if carried out in the last 5 months before shearing, or if the same sheep received repeated treatments.

The residue of synthetic pyrethroid retained in the fleece after dipping or long wool backliner application increased as the length of the wool increased at treatment, and appeared generally consistent with label recommendations. Current long wool backline products usually left residues of synthetic pyrethroid above 10 mg/kg on the wool. Short wool dipping left less than 10 mg/kg wool while off-shears backliners usually left average residue concentrations of about 2 mg/kg wool.

Although the actual on-farm results vary 4-fold above and below the average, the model can be used to estimate the expected residue concentration and likely range of results from most standard on-farm organophosphate and synthetic pyrethroid treatments. This will allow improved provision of advice so that most producers can meet specified industry standards. It will allow wool buyers to estimate the risk of purchasing high residue wool based on producers' statements about treatments applied.

Introduction

Several surveys of organophosphate (OP) and synthetic pyrethroid (SP) pesticide residues on greasy wool (Pattinson 1995; Plant 1995; Horton *et al*. 1997) have shown that substantial residues may remain on the shorn wool following treatments such as long wool shower or plunge dipping, jetting sheep close to the next shearing or repeated applications in long wool. These results have been supported by experimental studies (Campbell *et al*. 1995) that have shown that some treatments of sheep in

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long wool carried out strictly according to manufacturers' recommendations as specified on the label can leave high residues at shearing. In some cases this may result in high levels of pesticide in wool scour effluent that may exceed environmental standards for effluent disposal, with potential danger for Australian wool markets (Russell 1994; Pattinson 1995; Shaw 1997).

Wool producers can be advised to avoid methods or times of treatment that will leave very high wool residues, but it is more difficult to provide clear advice regarding methods in common use that may leave moderate concentrations of pesticide in the wool at shearing (2–10 mg/kg wool). If wool producers want to market their wool as widely as possible, or to target specific markets, they must have more precise advice about the risks and benefits of particular treatments (Russell 1994; Russell *et al*. 1995; Shaw 1997).

Organophosphate residue data from Tasmania (Horton *et al*. 1997) were analysed by a simple model, which did not take into account the known rate of OP breakdown. Campbell *et al*. (1998) showed that the rate of breakdown depends on the method of application, and the rate decreases over time. In addition, their study showed that the amount of pesticide taken up by the wool depended on the length of the wool at the time of application. These factors were not included in the analysis by Horton *et al*. (1997).

In the study reported here farmer records of insecticide treatments used on sheep at known times were related to the insecticide residues in their wool at shearing. The intention was to produce a mathematical model that could predict the likely consequences of on-farm treatments at any time throughout the wool-growing cycle, and to determine how late an insecticide could be applied to sheep without creating excessive residues at shearing.

Materials and methods

Surveys

All surveys were carried out by selecting random samples of fleece sale lots to be tested for OP and SP pesticide residues. Pesticide concentrations in the wool samples were measured by the State Chemistry Laboratory, Victoria (National and Tasmanian surveys), or by the Queensland Department of Primary Industry Chemical Residues Laboratory (Queensland survey). Where possible, the owners of the fleece lines were identified and requested to supply information on the treatments that had been applied to the sheep that produced the sampled wool.

A National survey (Plant 1995) was carried out by mail from November 1992 to May 1994 with about 75% response rate for identified growers and 735 usable responses. The Tasmanian survey (Horton *et al*. 1995, 1997) was undertaken by personal interview during 1993–94 and had a 100% response rate of the 85% of lots for which an owner could be identified (170 usable responses). The Queensland survey (Armstrong and Ward 1998) was a mail survey using a questionnaire, similar to the National survey, but with data obtained in 1995–97 (300 usable responses).

Data collection

Data were included only if one or more pesticides had been used on the sheep and those pesticides and no others were detected in the wool (except trace amounts), if details of methods and time of treatment were available, and no more than 3 treatments were applied to the sheep. For 10% of the samples the chemical detected did not match the chemical in the pesticide that was stated to have been applied, so these were discarded. After initial analyses another 5% of results were rejected because they differed from the expected results by a factor of 15 or more. These were not consistent with the other survey data nor with experimental results (Campbell *et al*. 1998), and were clearly due to misreporting of treatments applied or the time of application.

Samples for which OP backliners were used were eliminated as these gave excessively variable results, possibly due to very rapid breakdown (Campbell *et al*. 1998). Use of a firefighter apparatus for pesticide application (by squirting the sheep directly from the fire hose) also gave extremely variable results. This is not a registered method of treatment so these samples were also excluded.

Where 2 different chemicals were used and detected separately, they were treated as 2 independent results. Where the same chemical was used on more than one occasion, the effects were assumed to be independent but additive. Organophosphates were commonly used several times, so it was more efficient to include the multiple treatments. However, SPs were rarely used repeatedly, so data from the few cases of repeated use of the same SPs were excluded.

The only OPs for which adequate data were available were diazinon (323 samples), propetamphos (29 samples) and coumaphos (11 samples, all shower dip). The SPs for which adequate data were available included alphacypermethrin (77 samples), cypermethrin (97 samples), deltamethrin (70 samples, all off-shears backliner) and cyhalothrin (15 samples, all short wool dipping). In some cases laboratory reports did not distinguish alphacypermethrin from cypermethrin, but this was determined from the owners' statement of the product used.

Variables considered in the model

Time between treatment and the next shearing. The Tasmanian survey asked respondents for the actual dates of the previous shearing and the next shearing (at which the wool sample was taken) and the date of the treatment. In many cases this information was only accurate to the nearest month. In the National and Queensland surveys the respondents were asked how many months wool were on the sheep at shearing (to the nearest month). The time between the previous shearing and treatment was coded using the following categories: within 24 h, 24 h–3 weeks, 3–5 weeks, 6–11 weeks, 3–5 months, 6–9 months, 10–12 months. The model uses the number of days from shearing to treatment and from treatment to the next shearing, so all of these time points were coded to the midpoint of the period. There is an error of up to 2 months for the 6–9 months wool treatments.

Wool growth variation between states. The pesticide breakdown rate is calculated from the total amount on the sheep, not the concentration in the wool because this depends on wool growth. Therefore it is necessary to convert the residue result in mg per kg greasy wool to mg chemical per sheep. The average state fleece weights for 1991–95 (ABARE 1997) were assumed for sheep with 12 months wool (SA 5.01 kg, WA 4.55 kg, NSW 4.41 kg, Qld 4.33 kg, Vic. 4.25 kg, Tas. 3.82 kg). For sheep shorn with less than 12 months wool, linear growth during the year was assumed. In addition it was assumed that 0.35 kg of wool remained on the sheep after shearing, so the pesticide on the sheep at any time was distributed among the amount calculated above plus 0.35 kg. The wool left after shearing is based on 100 mm growth each year with 7 mm left after shearing, or 7% of a 5 kg fleece.

Amount of organophosphate or synthetic pyrethroid effectively applied by different methods and chemicals. Separate variables were used for the mass of OP effectively applied by hand jetting, jetting race, spray race or dipping. For SPs the variables were for the mass effectively applied by shower or plunge dipping, hand jetting or spray race, off-shears backliner and backliner in long wool. This estimates the mass of pesticide retained in the wool immediately after treatment, not necessarily the amount applied to the sheep.

Length of wool and amount applied. It was assumed that the mass of pesticide retained in the fleece could vary depending on the length of wool at the time of treatment. This was modelled using the variables W1, W2 and A0.

W1 allowed for an increase in the amount of pesticide taken up by the wool as a function of the length of the wool at the time of application:

$$W1 = FW/(W + FW)$$

where FW is the proportion of 12 month fleece weight at the time of treatment and W is the wool application variable, in the range 0–1.

When W = 0, W1 is not affected by length of wool at the time of treatment. When W is low, the amount taken up by the wool increases rapidly soon after shearing. When W = 1, the pesticide taken into the wool is directly proportional to the wool length.

W2 is an estimate of the average amount of pesticide applied by producers at a specific time as a proportion of the maximum that could be applied. It is in the range 0–1, changing at a constant rate from one shearing to the next. W2 is not intended to represent the 'recommended rate', it is simply a variable used to account for the fact that producers may increase or decrease their application in a consistent manner as the length of wool increases or the next shearing approaches.

The variable A0 controls the estimate of the maximum amount that could be taken up by the wool by any given treatment method. This is not necessarily the maximum actually applied on-farm at any time as the combination of variables might cause the maximum to be estimated to occur in 12 months wool, a situation for which no survey data were available. Care must be taken not to extrapolate the application rate model beyond the data on which it is based.

The estimate (mg/sheep) of the amount of pesticide taken up by the wool is

$$\text{Estimate} = A0 \times W1 \times W2$$

Pesticide residue on wool on any day after treatment. The rate of breakdown has been shown to change over time, from a faster initial rate to a slower steady-state rate, so each day of pesticide breakdown was considered consecutively using the model developed previously (Campbell *et al*. 1998).

Fitting the model to the data. For each pesticide group the model could have a large number of variables although not all values could be estimated for every pesticide. The amount effectively applied depends on the method of application and the length of wool at the time of application. The amount effectively applied may vary between states and the rate of breakdown may vary between states.

Table 1. Variables controlling the rate of breakdown of pesticides applied to fleece wool

OP, organophosphate; SP, synthetic pyrethroid
f is the proportion of chemical remaining from one day to the next: f_s is the final breakdown rate, f_0 is the initial rate for pesticide applied off-shears, f_i is the initial rate for pesticide applied to very long wool; k_f indicates the rate at which f_0 changes to f_i (high values indicate a rapid change); c_t controls the rate at which the initial rate changes to f_s
The model did not permit values of k_f or c_t greater than 20
Values set by the model to be the same as the value above are indicated by ditto marks

Method	f_s	f_0	f_i	k_f	c_t
OP plunge dipping ≤42 days	0.989	0.874	0.980	4.7	13.0
OP plunge dipping ≥122 days[A]	”	”	”	”	4.8
OP hand jetting	”	”	”	”	4.3
OP automatic jetting race	”	”	”	2.9	2.7
SP jetting	0.995	0.967	0.987	20.0	20.0
SP long wool backliner	”	”	”	20.0	1.1
SP short wool backliner	”	”	n.a.	n.a.	5.8

[A] A linear change in c_t was used between 42 and 122 days.
n.a., values not applicable to the treatment method.

All of these variables are interrelated and cannot be optimised independently of each other by the model. A genetic algorithm (Horton 1996; Campbell *et al*. 1998) was used to allow all the model's variables to change over a wide range simultaneously until a set was found that best fitted the data (using least squares on a logarithmic scale). The genetic algorithm method is very robust in that it can fit a non-linear model to the data, using a wide range of disparate but related variables. The resulting model should be very close to the best possible fit to the data, using the defined assumptions.

The genetic algorithm used a population of 100–150 individual test strategies with fitness sharing (Goldberg *et al*. 1992) to avoid premature convergence. After 100–200 generations, 'parallel hill-climbing' (Mahfoud 1995) was used to obtain a group of potentially good options. The upper and lower limits for each variable allowed by the genetic algorithm were then narrowed to fit the best group of potential results and the genetic algorithm was re-run with a fresh population to define the variables more closely until little further improvement occurred in fitting the model to the data.

Results

The model

The pesticide concentration on greasy wool (mg/kg greasy wool) is estimated as follows:

$$\text{Pesticide residue concentration} = r_n/(\text{GFW} + 0.35)$$

where GFW is the greasy fleece weight at shearing, and the extra 0.35 kg allows for wool remaining on the sheep after shearing. Where the fleece weight is not known the model assumes a 5 kg fleece, or if the state of origin is known it uses average fleece weights given in the Materials and methods. GFW is adjusted linearly for more or less than 12 months wool if necessary.

The variable r_n is the total pesticide on the sheep n days after treatment, obtained from:

$$r_{d+1} = r_d \times f_d$$

where r_d is pesticide on the sheep (mg/sheep) d days after treatment; r_0 is mg pesticide applied per sheep (on day 0) where

$$r_0 = \text{A0} \times \text{W2} \times \text{FW}/(\text{W} + \text{FW})$$

where

$$\text{FW} = t \times 5 + 0.35$$

where t is time from previous shearing to treatment in years. f_d is proportion of pesticide left after 1 day of breakdown:

$$f_d = f_s + (f_t - f_s) \times e^{-c_t y}$$

where y is time since treatment in years; and f_t is the initial breakdown rate for pesticide applied to wool at time t after shearing:

$$f_t = f_i + (f_0 - f_i) \times e^{-k_f t}$$

Table 1 shows values for f_0, f_s, f_i, k_f and c_t for each of the chemical groups and each treatment method. These were derived by the method of Campbell *et al*. (1998) using the long wool experiments in that report, together with further short wool experiments (N. Campbell, P. Morcombe, R. Armstrong, J. Karlsson, P. Spicer and B. Horton unpublished data). Values for A0, W and W2 are given in Table 2 (OPs) and Table 3 (SPs).

Producers' statement of amount used

The Tasmanian survey had included an estimate by the producer of the amount or concentration used as a percentage of the recommended dose. About 80% of producers claimed to have used the correct concentration, with the others evenly divided between lower rates (usually 50%) and higher rates (usually 150–200%). Preliminary analysis showed that the

Table 2. Best fit model for application of organophosphates on-farm

The amount of pesticide applied (mg/sheep) = A0 x W1 x W2, where W1 = FW/(W + FW) and FW is the proportion of a 12 month fleece at the time of treatment; W2 changes linearly from the value at day 0 to the value at day 365

Ditto marks indicate that the model used the same value as the above for this treatment

Values for A0, W and W2 for multiple treatments are the same as those for each of the individual treatments applied

Method of treatment	No. of lots tested	A0	W	W2 at day 0	W2 at day 365	s.d. (as a factor)	Estimated amount applied (mg/sheep) Off-shears	6 weeks	6 months
Plunge dip	46	15000[A]	0.68	0.73	1.00	4.2	1500	3600	
Shower dip	96	”	”	”	”	2.9	”	”	
Hand jetting	76	1160	0	1.00	0	3.6			580
Jetting race	37	1830	0	1.00	0	4.7			920
Spray race	9	680	”	”	”	2.6			340
Dip + dip or jet[B]	46					3.6			
Jet + jet or spray race[B]	52					5.4			
Other combinations[B]	1								
All records	363					3.8			

[A] The ‘maximum amount applied’ for dipping is used by the formula above to determine the actual amount taken up by the wool at any time within the period covered by the survey results. In the case of dipping the amount shown is a theoretical amount for sheep with 12 months wool growth. The actual amounts applied by dipping were less than 5 g for the time periods in this study.

[B] Standard deviations were calculated separately for single treatments and for combinations of treatments; most combinations were either dipping followed by a further dipping or jetting, or a series of jetting/spray race treatments

producers’ estimate was not related to the resulting residue, so the concentration stated was ignored in further analysis. The National survey had a more general question relating to the amount used, and most stated that they used the correct amount, although this was not tested for significance. There is also a wide variation for those results where the producer stated that the recommended rate was used, so producers’ statements of application rate may not be reliable.

Differences between chemicals applied

No significant difference could be found between different OP chemicals (diazinon, propetamphos, coumaphos) in the amount effectively applied, but there were very few cases using propetamphos or coumaphos. Nor was there any significant difference between the SPs (alphacypermethrin, cypermethrin, deltamethrin and cyhalothrin). For the final analyses reported here all chemicals within a group were treated as equivalent. For the OPs there is little difference in the recommended rate for the different chemicals, but for the SPs the rate on the label is lower for deltamethrin than for the other off-shears backliners. The differences in SP residues were consistent with the differences in dose rate, but they were so variable that they were not statistically significant. For SPs used off-shears followed by shearing 12 months later the mean residues (± s.e.) were 2.53 ± 0.39, 2.50 ± 0.33 and 1.89 ± 0.92 for alphacypermethrin, cypermethrin and deltamethrin respectively.

Table 3. Best fit model for application of synthetic pyrethroids on-farm

The amount of pesticide applied (mg/sheep) = A0 x W1 x W2, where W1 = FW/(W + FW) and FW is the proportion of a 12 month fleece at the time of treatment; W2 changes linearly from the value at day 0 to the value at day 365

Method of treatment	No. of lots tested	A0	W	W2 at day 0	W2 at day 365	s.d. (as a factor)	Estimated amount applied (mg/sheep) Off-shears	6 weeks	6 months
Off-shears backliner	205	230	n.a.	n.a.	n.a.	3.4	230		
Dip or jet	30	210	0	0.31	1.00	3.4	66	83	
Long wool backliner	22	910	0	1.00	1.00	2.9			910
All records	257					3.4			

n.a., values for W and W2 are not applicable for treatment applied only off-shears.

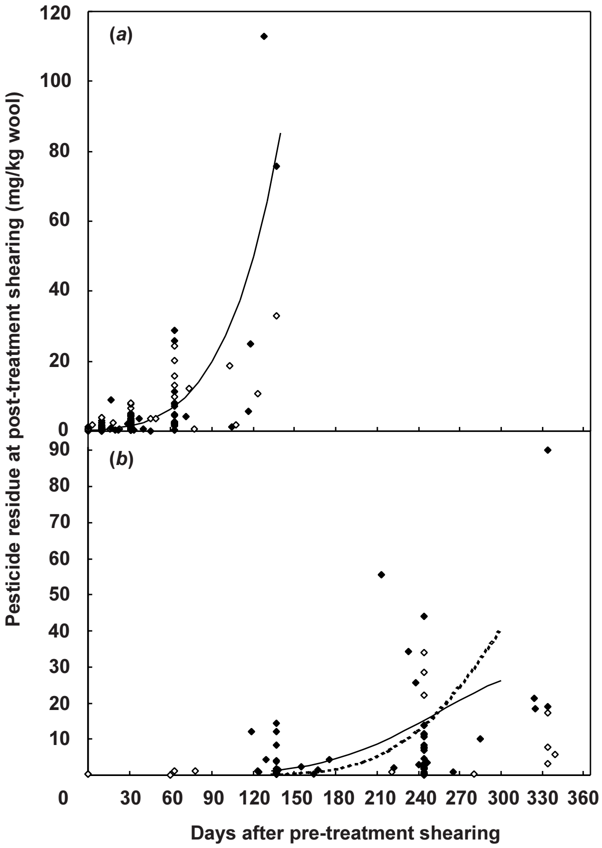

Figure 1. Pesticide on sheep at shearing after organophosphate application. (*a*) Plunge dipping (◆) or shower dipping (◇); (*b*) hand jetting (——, ◆) or jetting race (┈┈ , ◇).

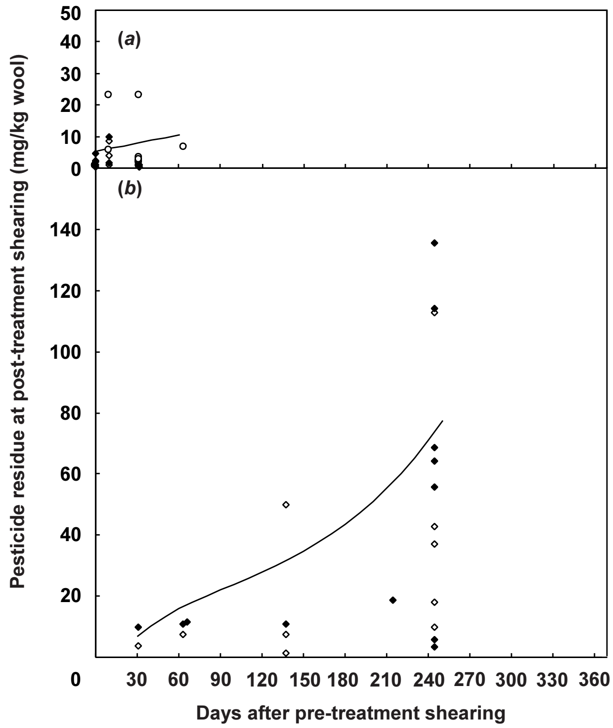

Figure 2. Pesticide on sheep at shearing after synthetic pyrethroid application. (*a*) Dipping or jetting with alphacypermethrin (◆), cypermethrin (◇) or cyhalothrin (○); (*b*) long wool backliners—alphacypermethrin (◆) or cypermethrin (◇).

Differences between states

There were some differences in OP and SP residues between states that could be due to differences in the amount applied or in breakdown rate or both. However, these differences were not always consistent with the assumption that breakdown should be faster in hotter areas (Rammell and Bentley 1989), and the differences were small compared with the overall variation. State differences were not included in the final analysis.

Accuracy of the results

The laboratories reported results in mg/kg wool grease or mg/kg wool to an accuracy equivalent to the nearest 0.1–0.2 mg/kg OP or SP in greasy wool. Most producers who stated that they had not used a SP had no SP detected in the wool. However, there was a low level of OP in about 75% of cases in which no OP had been used, with a median concentration of 0.84 mg/kg. This is consistent with the OP residue level expected if these flocks contained some individually treated struck sheep. However, results below about 1 mg/kg could not be accurately distinguished from background concentrations.

The background level of OPs prevented accurate modelling of methods that would result in very low levels of residues. For this purpose further experimental studies are needed on short wool treatments and further surveys using wool samples with more precise information about treatments used. This work is currently in progress.

Degree of fit to the data

The genetic algorithm does not permit the usual method of determining the significance of each individual variable used. However, the model as a whole can be checked by measuring the correlation against the original data. The relevance of individual options can be tested by including or omitting them to test their importance to the model. The correlation was 0.53 for

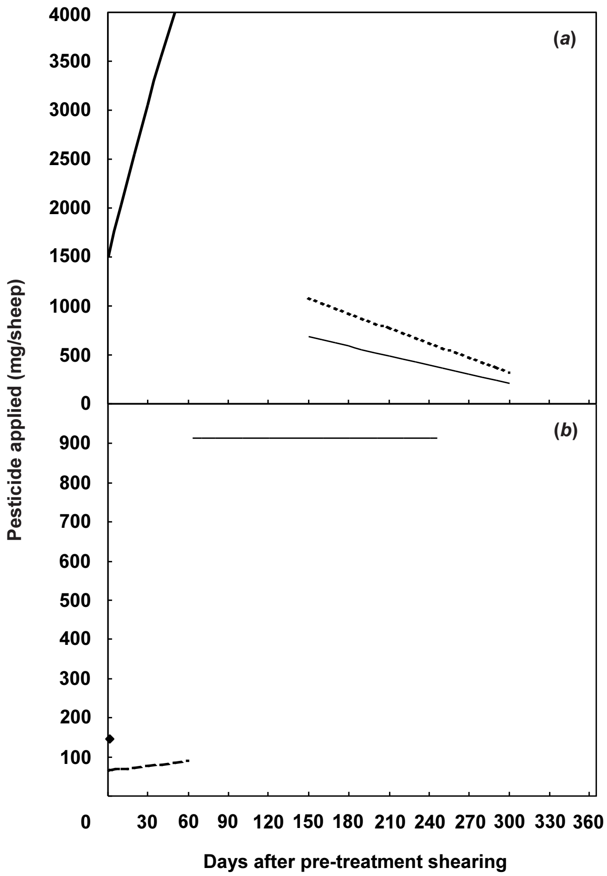

Figure 3. Estimated amount of pesticide taken up by the wool. (*a*) Organophosphate dipping (——), hand jetting (——) or jetting race (·······); (*b*) synthetic pyrethroid off-shears backliner (◆), long wool backliner (——) or dipping (- - - -).

OPs and 0.53 for SPs. These correlations are highly significant (P<0.001) although they indicate a large degree of variation between farms that is not accounted for in the model.

This leaves considerable unexplained variation. There was a standard deviation for estimated pesticide residue concentration on greasy wool on the $\log_{10}$ scale of 0.58 for OPs and 0.53 for SPs. Therefore any estimate of expected residue from a known treatment has a possible error of a factor of 3.8 for OPs and 3.4 for SPs (Tables 2 and 3). This means that an estimate of the residue following a known treatment may be almost one-quarter of the true result or nearly 4 times higher (one standard deviation above and below the geometric mean). This is seen in Figures 1 and 2, where data points from the same method at the same time period often cover a range with a factor of more than 10 on the $\log_{10}$ scale. The fitted curve shows the arithmetic mean, which is about double the geometric mean for this data.

The OP graphs omit nearly half the data that were used in the analysis, since points would be misleading on the scatter-plot where more than one treatment was given, or where the sheep were not shorn in 12 months wool.

Residues on the wool

The average residue concentration left by OP plunge dipping was >10 mg/kg wool if there was a delay of more than 72 days between shearing and treatment. Plunge and shower dipping is only a registered treatment provided it is carried out within 6 weeks after shearing. At 6 weeks the average residue is 2.8 mg/kg wool. Residues from OP jetting at this time were much lower, but residues >10 mg/kg occurred if jetting was not carried out until more than 7 months after the previous shearing.

Long wool SP backliner treatment had an average residue concentration >10 mg/kg if applied more than 1.5 months after shearing. The short wool treatments left lower concentrations, but residue from SP dipping more than 2.5 months after shearing had an average concentration >10 mg/kg. The off-shears backliner treatment left the lowest residues in this group, with an arithmetic mean of 2.3 mg/kg and few samples >5 mg/kg.

Amount of chemical taken up by the wool

Figure 3*a* shows the amount of OP estimated to have been taken up by the wool by each method. For plunge or shower dipping, this amount increased rapidly as the length of wool increased for the first 2 months after shearing. There was insufficient data available to determine the amount of OP taken up by the wool after dipping in more than 3–4 months wool.

In contrast to the situation with OP dipping, the model suggested that there was less chemical retained following OP jetting treatment as the length of the wool increased. The model indicated that the amount taken up by the wool after using a jetting race was greater than that for hand jetting.

Figure 3*b* shows the amount of SP that the model indicated was effectively applied by the average producer using each method. For SP dipping, this amount increased as the length of the wool increased, but the amount effectively applied by dipping or off-shears backliner was much less than the amount applied by long wool backline treatment.

Three litres of OP pesticide at the recommended concentration for the common pesticides contains 300 mg OP (dipping for lice), 600 mg (dipping to

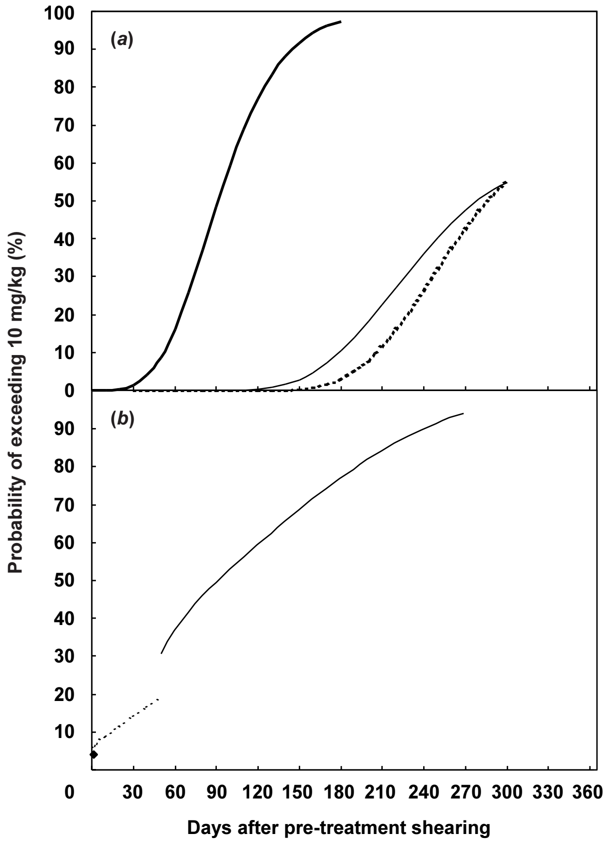

Figure 4. Probability that an on-farm treatment will leave wool pesticide residues exceeding 10 mg/kg organophosphate or synthetic pyrethroid. (*a*) Organophosphate plunge or shower dipping (——), hand jetting (——) or jetting race (········); (*b*) synthetic pyrethroid short wool backliner (◆), plunge or shower dipping or jetting (·······), long wool backliner (——).

prevent flystrike) or 1200 mg (jetting to prevent flystrike). In actual practice the amount of OP taken up after dipping was much more than the amount in 3 L, while for OP jetting it was much less, particularly in long wool. The amounts effectively applied by SP treatment were closer to the recommended rates (60–120 mg for 3 L dipping, 100–250 mg for off-shears backliners or 1000–1575 mg for long wool backliners applied to sheep with greater than 4 months wool).

Probability of exceeding a specified residue concentration

There is a high degree of variation in the results indicated by the model, so it is not possible to give an exact prediction of expected residues. However, wool producers may be more concerned with their individual risk of exceeding a specified concentration rather than the average value of all producers using a given treatment. Figure 4 shows the probability of any given treatment exceeding 10 mg/kg OP or SP. Wool producers who wish to remain below specific target concentrations may be able to use this information to assess the risk of certain treatments. Wool buyers may be able to use average values for most purposes because they combine large numbers of lots for processing, but they may need to know the risk of any single lot exceeding some upper limit. The model can be used to advise on the risk of specific procedures or treatment times.

For OP plunge or shower dipping, the risk of high residues rises rapidly after 42 days, the latest time for which this treatment is registered. For jetting the probability of high residues rises (more slowly) if it is used more than 6–7 months after shearing.

Synthetic pyrethroid off-shears backliners have a low risk of exceeding 10 mg/kg, while SP dipping or jetting also has a low risk if carried out within 6 weeks of shearing. However, with long wool SP backliner treatment there is a high probability of exceeding 10 mg/kg even if it is applied well before the next shearing.

Discussion

Use of the appropriate breakdown rates to interpret the survey data provided an estimate of the amount of chemical actually taken up by the wool following various applications by producers. This suggested that the amount applied by dipping increases substantially as the length of the wool increases. This would be a result of the increased volume of wool and wool grease on the sheep retaining a larger volume of dip wash and from stripping effects (O’Neill and Hebden 1968). In longer wool there is also a greater protection of the chemical from environmental effects on the breakdown rate. The OP or SP residue resulting from plunge or shower dipping in 6 weeks wool was more than double that from off-shears dipping. This highlights the need for dipping as soon as possible after shearing and in no case should it be used in long wool, since the amount taken up by the wool is very high and the time available for breakdown is shorter. The results suggest that the wool on each individual sheep takes up OP from the equivalent of an extra several litres of dipping solution due to a high level of stripping.

The amount of OP taken up by the wool after hand jetting or treatment by jetting race appeared to decrease slightly as the length of wool increased. This is unexpected because the standard recommendation is to apply more chemical in longer wool. Producers may apply more chemical to sheep that need a long period of protection before the next shearing, they may apply it more carefully if there is less wool to take up the chemical, or they may apply it primarily to the body in short wool and to the breech in longer wool—this would vary the amount applied to the fleece without changing the amount applied to the sheep. The amount taken up by the wool in most cases was much less than the actual OP in the recommended volume of jetting mix. Further studies may be needed to determine whether this amount is adequate for the protection required. For most pesticides the label specifies the concentration of the jetting mix, but does not indicate the volume of chemical that should be applied by jetting. Therefore these results do not imply off-label use of any products.

Levot and Sales (1997) showed that 16 weeks after treatment using a standard jetting race, the level of OP in core samples of the combined fleeces was below the laboratory detection limit. Farm treatments leaving such low levels could have been omitted from the analysis if no other OP had been used on the sheep, or they may have been indistinguishable from the background OP concentration due to the inclusion of some individually treated struck sheep. However, any samples with high residue concentration would have been included although the result might be due to incorrect reporting of the time or method of treatment. Therefore the results for jetting more than 4 months before shearing may be biased by the inclusion of some erroneous high residues and exclusion or overestimation of genuine low residues. As a result the model is probably overestimating the amount of pesticide effectively applied by jetting, particularly by jetting races and the model should not be considered accurate for sheep jetted that have much less than 6 months wool.

The results suggest that more OP was taken up by the wool after application by jetting race than by hand jetting. This is not consistent with experimental studies of hand jetting and automatic jetting races (Levot and Sales 1997) where hand jetting gave a much higher application rate than from an automatic jetting race. This could be a result of bias in selection or rejection of samples with very low residues as described above. However, the result shown here could be typical of farm use. Those using hand jetting may generally apply most of the chemical to the breech, while jetting races may apply proportionately more to the back (and hence more to fleece wool).

Many producers treat flocks containing some flystruck sheep with a mixture of cyromazine and an OP. The concentration of cyromazine in the wool was not measured in these surveys, so all these results were coded as OP treatment for this analysis. However, it is likely that when such a mixture is used, the OP concentration in the mixture may be less than the label concentration, or may be less likely to be above the recommended concentration. A review of the original data suggested that in cases where this mixture was used the wool had about half the OP residue level compared with the use of an OP alone.

It is also likely that research staff carrying out experiments on hand jetting apply much more chemical than is commonly used on-farm, since survey residues after hand jetting are almost invariably lower than observed in comparable experimental studies. It would be expected that farm staff with hundreds or thousands of sheep to hand jet might be less fastidious about the volume of jetting fluid applied than research staff intent on replicating recommended treatment rates. In contrast, automatic jetting races used on-farm might give similar applications to those in experimental use, provided the chemical is mixed at the same rate.

The amounts applied by both jetting methods appear to have been quite low, considering that the standard recommendation is to apply 0.5 L of jetting fluid per month of wool growth. This is probably sufficient to control lice by jetting (P. Morcombe pers. comm.), but may be excessive for flystrike control, since only limited target areas on the sheep need protection. Wool producers may routinely apply much less than this rate or they may apply most to the breech of the sheep and little to the fleece. Surveys in Tasmania (B. J. Horton and D. J. Best unpublished data) indicate that most producers use only 1–2 L per sheep, and they vary widely in how much of this is applied to the fleece wool.

The results for SPs were reasonably consistent with the amounts recommended. With dipping and jetting there is a chance of errors in making up the required mixture or applying the wrong dose rate, but most SPs are applied by backliner application, where such errors are less likely to occur. Synthetic pyrethroids strip less than OPs, so in the case of dipping or jetting with an SP the amount of chemical applied is more closely related to the amount of liquid applied.

An important finding was the inconsistency between the chemical stated to have been used and the chemical detected in 10% of cases, and the obvious inconsistency between the amount of chemical detected and the treatment used in a further 5%. It is clear that many producers do not have adequate records of treatments used. This has implications if wool buyers rely on statements from producers about the likely pesticide residues in the wool.

For all methods and chemicals there was a very high level of variation after allowing for the method of application, length of wool, and time from treatment to shearing. This may be a result of wide variation in application technique causing variation in the amount retained in the wool, or variation in the concentration of chemical applied to the sheep. Variation in application methods could also alter the proportions of chemical applied deep into the wool or close to the surface. This would change the degradation rate and the amount of residue left at shearing. The variation in results may also reflect the poor accuracy of records of method and time of treatment. This study is intended to assist producers in estimating likely residues from their treatments, and also to assist wool buyers to predict residues from stated treatments. If there are inaccuracies in the farm data that increase the level of variation in these surveys, then the same inaccuracies will apply when producers attempt to estimate their own residues or prepare declarations for use by buyers. Therefore the results presented here are a valid reflection of the current situation on-farm. Wool buyers who rely on statements by producers that are not supported by adequate records or by actual wool residue tests should expect the high level of variation reported here. Further investigations are being carried out to determine whether there is less variation using data from producers who keep accurate records of all chemical treatments.

The range of residue levels associated with various methods of application of different chemicals are not fully consistent with the results obtained under experimental conditions, where it is reasonable to assume the correct amount of chemical was applied in the correct manner. The generally lower levels obtained in farm surveys indicate that in some cases wool producers are applying chemical in an inefficient manner and there is room for considerable improvement. The correct application of the chemicals would result in better control or protection and reduce the need for late season treatments. Late season treatment makes a major contribution to the total residue in the Australian wool clip.

The actual residue concentration obtained on-farm may vary nearly 4-fold from the average concentrations indicated by the model. However, the wide range of treatment methods and times of application may result in residues in some cases as low as 0.1 mg/kg or for other treatments higher than 100 mg/kg, so the model can predict low, medium and high concentrations adequately.

Wool buyers will be mixing large numbers of lots of wool for each day's processing, so for most purposes they will be interested in the average result of specified treatments rather than results for individual lots, provided the worst extremes are avoided.

Individual wool growers will not be able to predict exact residue levels from their treatments, but they can estimate the risk that certain treatments will result in unacceptable pesticide residue concentrations. They will need to balance this risk against the need for lice or flystrike control at a given time. More care in carrying out these procedures and more accurate recording of treatments applied should improve the ability of the model to predict expected pesticide residue concentrations from on-farm treatments. It is anticipated that the model will be improved over time as more data and more reliable on-farm information becomes available.

Conclusions

Treatments likely to result in average OP or SP concentrations less than 10 mg/kg greasy wool are: (i) OP or SP dipping within the registration period of 6 weeks after the previous shearing; (ii) OP jetting more than 5 months before the next shearing; and (iii) off-shears SP backliner. Any SP long wool backliner treatment is likely to exceed 10 mg/kg greasy wool.

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References

ABARE (1997). 'Agricultural Commodity Statistics.' (Australian Bureau of Agricultural and Resource Economics: Canberra.)

Armstrong, R. T. F., and Ward, M. P. (1998). Recent experiences with wool residues. *In* 'Proceedings of the Australian Sheep Veterinary Society, Australian Veterinary Association Conference'. Sydney. (Ed. T. J. Watts.) pp. 89–93. (Australian Veterinary Society: Indooroopilly, Qld.)

Campbell, N. J., Hanrahan, P. D., Russell, I. M., Roberts, G. S., and Horton, B. J. (1998). Modelling pesticide residues on greasy wool: experimental studies. *Australian Journal of Experimental Agriculture* **38**, 441–9.

Campbell, N. J., Russell, I. M., Hanrahan, P. D., Nunn, C. R., Roberts, G. S., and Tawfik, F. (1995). Pesticide residues in wool after late season lice and fly treatments. *In* 'Proceedings of the Australian Sheep Veterinary Society, Australian Veterinary Association Conference'. Melbourne. (Ed. J. Cox.) pp. 112–15. (Australian Veterinary Society: Indooroopilly, Qld.)

Goldberg, D. E., Deb, K., and Horn, J. (1992). Massive multimodality, deception and genetic algorithms. *In* 'Parallel Problem Solving from Nature, 2'. (Eds R. Manner and B. Manderick.) pp. 37–46. (Elsevier Science Publishers: North Holland, Amsterdam.)

Horton, B. (1996). A method of using a genetic algorithm to examine the optimum structure of the Australian sheep breeding industry: open-nucleus breeding systems, MOET and AI. *Australian Journal of Experimental Agriculture* **36**, 249–58.

Horton, B., Best, D., Butler, L., and Gregory, G. (1997). Organophosphorus residues in wool grease resulting from specified on-farm lice and flystrike control treatments. *Australian Veterinary Journal* **75**, 500–3.

Horton, B. J., Gregory, G. G., and Best, D. J. (1995). Which lice and flystrike control procedures lead to high pesticide residue concentrations in wool? Results of a Tasmanian survey. *In* 'Proceedings of the Australian Sheep Veterinary Society, Australian Veterinary Association Conference'. Melbourne. (Ed. J. Cox.) pp. 116–18. (Australian Sheep Veterinary Society: Indooroopilly, Qld.)

Levot, G. W., and Sales, N. (1997). Insecticide residues in wool from sheep jetted by hand and via automatic jetting races. *Australian Journal of Experimental Agriculture* **37**, 737–42.

Mahfoud, S. W. (1995). Niching methods for genetic algorithms. PhD Thesis, University of Illinois, USA.

O'Neill, D. K., and Hebden, S. P. (1968). Investigation of sheep dips. 3. The influence of breed on stripping and deposition in the fleece of diazinon. *Australian Veterinary Journal* **44**, 344–8.

Plant, J. W. (1995). On farm pesticide use and wool residue levels—a national survey. *In* 'Proceedings of the Australian Sheep Veterinary Society, Australian Veterinary Association Conference'. Melbourne. (Ed. J. Cox.) pp. 119–23. (Australian Sheep Veterinary Society: Indooroopilly, Qld.)

Pattinson, R. (1995). The marketing consequences of pesticide residues in wool and the results of the National residue monitoring program. *In* 'Proceedings of the Australian Sheep Veterinary Society, Australian Veterinary Association Conference.' Melbourne. (Ed. J. Cox.) pp. 102–5. (Australian Sheep Veterinary Society: Indooroopilly, Qld.)

Rammell, C. G., and Bentley, G. R. (1989). Decay rates of organophosphate residues in the fleeces of sheep dipped for flystrike control. *New Zealand Journal of Agricultural Research* **32**, 213–18.

Russell, I. (1994). Pesticides in wool: downstream consequences. *Wool Technology and Sheep Breeding* **42**, 344–9.

Russell, I. M., Campbell, N. J., Nunn, C. R., and Hanrahan, P. D., and Smith, G. C. (1995). Reduction of pesticide residues on the Australian wool clip. *In* 'Proceedings of the 9th International Wool Textile Research Conference'. Biella, Italy, Vol. 1. pp. 101–9. (Citta degi Studi/International Wool Secretariat: Biella, Italy.)

Shaw, T. (1997). Wool as a 'clean, green' fibre; the implications of pesticide residues in wool—a challenge for regulatory authorities, drug companies, wool processors, veterinarians and farmers. *In* 'Proceedings of the 4th International Congress for Sheep Veterinarians'. Armidale, University of New England, Publisher Australian Sheep Veterinary Society. (Ed. M. B. Allworth.) pp. 98–105. (Australian Sheep Veterinary Society: Indooroopilly, Qld.)

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