Chemical residue trends for Australian and New Zealand wool

Stephen Ranford1*, Paul Swan2 & Chikako van Koten1

Textile consumer trends towards improved product safety and high environmental standards have significantly influenced regulators in key consumer markets. The apparel wool industry sector has responded to regulators, and for three decades the Australia and New Zealand wool industries have managed advancements in ectoparasiticides and improved sheep treatments targeting high environmental, animal health and welfare standards leading to safe wool products. Australian and New Zealand chemical residue data from greasy wool have been consolidated and analysed for organophosphate, synthetic pyrethroid, insect growth regulator, neonicotinoid, macrocyclic lactone and spinosad active. Trend analysis has been applied to time domain data to evaluate advancements in ectoparasiticide technology after revising environmental, animal health and welfare standards. Analysis shows impacts from technology improvement, regulatory change and compliance by sheep farmers meeting or exceeding published European Union residue limits for regulated ectoparasiticides namely organochlorine, organophosphate, synthetic pyrethroid and insect growth regulators. Implications from advancements in ectoparasiticide technology, industry management and regulatory measures, include healthy sheep growing in clean pastoral environments with evidence of reduced wool residue levels which complement high and rising proportions of Australian and New Zealand wool fibre meeting European Union Ecolabel criteria.

Wool production has been a historically and culturally important contributor to the world market leaders such as Australia and New Zealand for around 200 years1, and also to the global wool textile industry. New Zealand produced an estimated $139 \times 10^6$ kg of greasy wool in 2018–2019, from 27.5 million sheep of which approximately 4.5% were Merino2. By comparison in the same period Australia generated $300 \times 10^6$ kg of greasy wool from 72.5 m sheep, of which approximately 85% were Merino or allied breed derived3.

Sheep farmers in both countries confront a wide range of animal health challenges, and typically apply veterinary chemicals for preventative health reasons4,5 and for remedial treatment of acute conditions, such as in the event of an injury. In the case of ectoparasiticide chemicals, which are used to treat external parasites, proprietary formulations are developed to generate both high levels of treatment efficacy for well-defined periods, and also known breakdown profiles for the active compounds. The latter underpin the mandatory withholding period definitions in product labels, as part of the regulatory approval schemes implemented in Australia6 and New Zealand7. The chemical treatments for managing ectoparasiticides usually contain carbon, hydrogen, oxygen and some contain sulphur, while a few contain fluorine, chlorine, iodine and phosphorous. These chemicals are often molecular ring structures and the simpler generic name is reflected in the chemical name. For example, cyromazine(CYR), an insect growth regulator, is a triazine ring structured chemical8.

These chemicals pose a challenge for the industry, in the context of human health (e.g. managing exposure of farm workers and wool handlers to residual chemicals on greasy wool), but also in early stage wool processing, where the wool grease containing these chemical actives is separated from clean wool. Over the past decades, regulators have applied increasingly stringent environmental discharge standards to wool processors in Asia9–14, North America15,16 and within and across the European Union (EU)17,18. In addition to these point of discharge regulations, consumer product eco-labels are now providing an additional compliance requirement for greasy wool producers.

The EU Ecolabel, or EU Flower, is a voluntary ecolabel scheme established in 1992 by the European Commission. It was implemented in 200919 as a voluntary ecolabel award scheme intended to promote products with a reduced environmental impact during their entire life cycle, and to provide consumers with accurate,
non-deceptive, science-based information on the environmental impact of products based on peer reviewed scientific principles.

Life cycle assessment (LCA) science has been developed comprehensively since 1992 and recently work has advanced by incorporating chemical toxicity impact categories into LCA assessments. Prior to 1992 the wool industries in both Australia and New Zealand had already implemented chemical residues surveys to assess the impact of new procedures and products with the aim of managing chemical residues. These initiatives have undoubtedly improved knowledge of chemical residue management.

With increasing concerns for the environment, monitoring is important for wool producers aiming to meet published pesticide residue limits. Legislation has lowered the acceptable chemical residues on wool, and some ectoparasitcides have been banned altogether. Because of this, the International Wool Textile Organisation (IWTO) saw a necessity to develop a method to test for chemical residues on greasy wool. Currently, a draft test method, IWTO DTM-59: 2009, outlines tests for the presence of four classes of chemical residues: organochlorine (OC), organophosphate (OP), synthetic pyrethroid (SP) and insect-growth regulator (IGR). Several industry surveys were carried out in Australia and New Zealand to establish systematic approaches to sampling, measuring, monitoring and reporting residue levels to the wool trade, processors, industry regulators and government authorities.

Factors influencing lower residue trends include, (i) training and education relevant to pesticide use, (ii) observance of withholding periods between active applications and shearing designed to enable breakdown of residues, (iii) compliance with recommended application rates and, (iv) managing registration of pesticide actives used in the agriculture sectors. Measured OC residues in the surveys confirm deregistration of all organochlorine sheep products 27 and 22 years ago (Australia and New Zealand), has culminated in no survey result greater than the limit of reporting over the last 18 years.

While this analysis of residue surveys focuses on greasy wool shorn from sheep it is important to note that wool cleaning technology has advanced and consequently residues in commercially scoured wool fibre are significantly lower than the EU greasy wool limits discussed here.

The EU Ecolabel scheme is part of the sustainable consumption and production policy of the European Community, which aims at reducing the negative impact of consumption and production on the environment, health, climate and natural resources. The scheme is intended to promote those products which have a high level of environmental performance through the use of the EU Ecolabel to limit the most significant environmental impacts of products during their whole life cycle. However, reflecting the constant evolution of veterinary pharmacology, a number of newer chemical classes in wide commercial use are not included in the EU-Ecolabel, such as CYR, imidacloprid (a neonicotinoid) (NEO), ivermectin (a macrocyclic lactone insecticide) (MLI)) and spinosad (SPI) ectoparasiticides.

The regulatory framework applying to veterinary chemicals used for parasite control in the Australian and New Zealand wool industries involves the Australian Government Pesticides and Veterinary Medicines Authority (APVMA) and the New Zealand Ministry of Primary Industries Agricultural Compounds and Veterinary Medicines (ACVM), as the government statutory bodies responsible for the management of approvals for agricultural and veterinary chemical products in the two countries. The approval process examines human, animal and environmental risks of the product covering physico-chemical properties, toxicology, phytotoxicity, hazard assessment, labelling and withholding periods required between animal treatment and shearing.

In support of the Australian and NZ regulatory processes, and as a means of monitoring compliance with product use labels, surveys of ectoparasiticide residue levels on greasy wool have been underway more-or-less continuously in Australia since 1992, and periodically in New Zealand since 1987, using internationally accepted testing and proficiency systems established over the past 30 years for determining the levels of chemical residues in wool based on scientific methods. The earlier surveys were followed with an Australian initiative to monitor the newer chemical actives such as IGR and more recently the NEO and SPI actives. Australian data have been collected in National Wool Residues Surveys (NWRS) since 1992 (with an exception of no survey conducted in 2009). New Zealand data are available in industry reports dated back to 1988 and since 2015 the National Council of New Zealand Wool Interests participated in the New Zealand Wool Residue Survey over 2 seasons to establish contemporary data which are available to both the New Zealand and Australian wool industries.

However, the aggregated results of these surveys have not been previously published, instead being used for government and industry approval processes and to introduce new handling practices and extend education programmes aimed at reducing and eliminating both environmental, human and animal toxicity impacts.

Nonetheless, the lack of published data has not prevented organisations such as MADE-BY from generating assessments of human and eco-toxicity levels from greasy apparel wool. Such tools are intended to shape brand, retailer and ultimately consumer fibre choices to the extent that the data underpinning their ratings is not representative, not contemporary, and not subject to peer review.

Accordingly, the purpose of this paper is to provide accessible data summarising the status for the Australian and New Zealand wool, by aggregating previously unpublished historical residue data with contemporary results to enable analysis of trends. These trends encompass industry initiatives for managing ectoparasitcides and provide updated information on wool from these countries complying with EU residue limits.

**Methods**

Wool harvested by shearers on farms was sampled from bales and tested for ectoparasiticide residues in each country by accredited and internationally licensed wool testing laboratories.

**Survey samples.** The surveys utilised in this study were conducted during the 1988 to 2019 period and involved sampling of greasy wool bales pre-sale and during an annual wool growing and selling season using
internationally accepted pre-sale wool bale coring regulations. Wool types represented include fleece wool types from adult sheep, lamb's wool and recently oddment types, such as bellies and pieces.

In Australia, industry surveys commenced in 1992 and from 2000 involved representative sampling of each wool type carried out in the 6 wool producing states. Each typically involved randomised collection and testing by the Australian Wool Testing Authority (AWTA) of between 300 and 600 samples (each sample taken represents a farm lot), stratified by month to adjust for the characteristic pattern of monthly wool auction offering in each state.

The New Zealand data set consists of two early wool industry surveys completed in 1988 (80 samples) and 1993 (84 samples), and a major survey of farm lots randomly collected in each of the 2015/2016 and 2016/2017 wool production seasons by New Zealand Wool Testing Authority (NZWTA). For this survey, as in the Australian surveys since 2000, sample collection was stratified by calendar month within each of the main growing regions to provide a representative selection of samples from across the country.

**Chemical testing.** The samples were blended and analysed in accordance with the International Wool Textile Organisation (IWTO) Draft Test Method DTM-59 to determine chemical residues on greasy wool. For this method, the limits of reporting (LoR) for each active are summarised in Table 1.

From 2000, Australian tests were conducted at a single laboratory (AWTA Limited, Melbourne, Australia), and to minimise risk and impact of interlaboratory differences, the New Zealand samples collected in 2015/16 and 2016/17 were also analysed at this same facility.

**Statistical analysis.** Frequencies at each concentration of the actives categories OP, SP, IGR, CYR, NEO, MLI, SPI covered in the 2016–2017 survey were analysed to determine the form of the residue distributions for recent wool data. The adjusted Fisher–Pearson coefficient of skewness (Eq. 1) and excess kurtosis (Eq. 2) where $Y$ is the mean, $s$ is the standard deviation, and $N$ is the number of data points, were calculated for the distributions along with mean and median estimates, to provide evidence of the degree of asymmetry of the distributions (skew), and the proportion of outliers.

$$\left(\sqrt{N(N−1)}/(N − 2) \times \left(\sum_{i=1}^{N} (Y_i − \bar{Y})^3 / N^2 / s^3 \right) \right)$$

$$\left(\left(\sum_{i=1}^{N} (Y_i − \bar{Y})^4 / N^3 / s^4 \right) − 3 \right)$$

The median is regarded as a robust statistic in a situation where there are substantially skewed distributions, such as large pesticide databases.

The mean and median residue concentration results were analysed each using locally weighted scatterplot smoothing regression (Lowess) by fitting polynomials to data with weighted least squares estimation, firstly for Australian data and thereafter with the addition of the more limited New Zealand data. The Lowess method provides smooth trend lines of mean and median residue levels of toxic chemical compounds, and the 95% confidence limits of the trends is used to indicate the level of uncertainty associated with the mean trend lines and residue predictions.

The Lowess model uses a goodness of fit summary statistic (Pseudo $R^2$, Eq. 3) similarly to $R^2$ in the simple linear regression approach. The residual standard error (RSE) is also calculated, which is the square root of mean residual sum of squares used to determine uncertainty of predictions.

$$\text{Pseudo } R^2 (\%) = \left(1 − \frac{\sum_{i=1}^{n} \text{residuals}^2 / \sum_{i=1}^{n} (y_i - \bar{y})^2 }{n} \right) \times 100$$

Similarly, smooth trend lines of percentages of surveyed samples with their mean residue concentrations lower than the EU-Ecolabel limits were obtained over the time domain with Lowess, together with the 95% confidence limits and goodness of fit summary statistics.

| Active                                                                 | LoR (ppm*) |
|-----------------------------------------------------------------------|------------|
| Total organochlorine (OC)                                             | 0.05       |
| Total synthetic pyrethroid (SP)                                       | 0.1        |
| Total organophosphate (OP)                                            | 0.1        |
| Sum (triflumuron + diflubenzuron + dicyclanil) (IGR3)                 | 1.0        |
| Cyromazine (CYR) or Spinosad (SPI)                                    | 1.0        |

Table 1. Limits of reporting for residues analysis. *ppm = mg/kg.
Ectoparasiticide residue distribution parameters. The distributions corresponding to each of the residue actives are shown in Fig. 1a–f, for the 2016–2017 Australian season with the corresponding descriptive statistics summarised in Table 3.

The results show residue concentration distributions for each active are strongly asymmetrical, with a high frequency of samples where residue levels are below or close to the limit of reporting, and a relatively small proportion of samples of high residue concentration level. For each active, the mean residue concentration level is much greater than the median value and exceeds the 90th percentile of observations. The values of skewness are large and positive and the high values for kurtosis indicate the tail outliers are extremely large values compared to the mean. Collectively, these distribution shape parameters indicate the data are not normal and the mean and standard deviation values for residue concentration will not be reliable or representative of typical residue values.

| Active | Applicable EU-Ecolabel limit (ppm) |
|--------|-----------------------------------|
| Total OC | 0.5 |
| Total SP | 0.5 |
| Total OP | 2.0 |
| Total IGR₃ | 2.0 |
| CYR | No limit |
| NEO | No limit |
| MLI | No limit |
| SPI | No limit |

Table 2. EU Eco-label criteria for pesticide concentrations on greasy wool as of June 2014.

Results

Table 2 lists the pesticide concentration limits for individual active compounds implemented by the EU-Ecolabel system, along with actives that have no limit in the EU which can be used for animal health in Australia and New Zealand. The table includes OC, once widely used, but is no longer registered for use by the statutory authorities in Australia and New Zealand.

Compliance with EU residue limits. The high rates of compliance for samples meeting EU residue limits shown in Fig. 4a, b are evident from each country for OP and SP. It is clear there are lower rates of compliance corresponding to IGR regulated by the EU (Fig. 4e) with Australian compliance close to 79% (2019) and New Zealand at 68% (2017). Based on the analyses over 10 years prior to 2019 the average annual percentage increase of EU compliant wool (wool meeting EU eco label criteria for all regulated actives, OP, SP and IGR₃ (3 actives)) from Australia was 3.2% (32% over 10 years) and the corresponding percentage when New Zealand data is included was 3.0% (30% over 10 years).

EU compliance for mean residue levels in Australian greasy farm lots for all OP, SP and IGR actives would be close to 100% in 7.5 years from 2019 and for New Zealand farm lots the expected timeline is 12 years based on the trends for the last decade. In Fig. 4d the three established IGR actives are a factor influencing the availability of compliant wool. Until 2007/08 season IGR₃ criterion increased to the sum of diflubenzuron + triflumuron. From 2008/09 season dicyclanil was added so the criterion increased to the sum of three insect growth regulators (IGR₃). However alternative actives, such as SPI, are replacing the IGRs, which is reflected in the upward trends for SPI in both countries. This is also the case for the NEO active which has very low median and mean
Discussion

The OP ectoparasiticide residues for both Australia and New Zealand greasy wool met the EU regulation maximum of 2 ppm over four recent harvesting seasons (2015/16, 2016/17, 2017/18, 2018/2019). Australian data, sampled over a longer period, has been EU compliant since changes were made to the regulations in 2002.

levels that are trending below 2 ppm in 2016–2017 and 2017–2018 seasons, and marginally above (2.2 ppm) in the latest 2018–2019 season.
Median SP residues for each of the countries are below the EU limit of 0.5 ppm and the corresponding mean data in Australia for the 2018/2019 season was marginally lower than the limit while the last measured New Zealand mean result in 2016/2017 was marginally higher. The downwards trend in SP residues in Australian and New Zealand greasy fleece wool over the last 25 years has undoubtedly been influenced by deregistration of products in the SP category of actives used in sheep treatments combined with a shift to other actives regarded as more effective, such as IGR products. For example, permethrin is not registered in APVMA approved products.

The means of the sum of three IGR (EU requirement) including dicyclanil, diflubenzuron and triflumuron are above the EU limit, however the median for both countries is lower than the EU limit. Dicyclanil has the higher use of these three IGR products in Australia based on APVMA registration data. In New Zealand, ACVM registered products indicate a larger use of diflubenzuron when considering the regulated IGRs. However, these actives are not popular in either of the two countries.

Residues of CYR, an IGR active which is not regulated in the EU, are present at levels below the sum of the mean residue levels of dicyclanil, diflubenzuron and triflumuron. The medians for CYR, which is a popular choice of IGRs in both countries, are also low. The residues of relatively new actives, including NEO, MLI and SPI, exhibit low mean values for both countries alongside low median results. The MLI chemical, ivermectin is a choice of IGRs in both countries, and exhibit low mean values for both countries alongside low median results. The MLI chemical, ivermectin is available in both Australia and New Zealand but usage is not as high as CYR.39,40.

Table 3. Summary statistics for wool residue distribution, Australia, 2016–2017.

| Active | Min | Max | Median | 75th | 90th | 95th | Mean | Skewness | Kurtosis |
|--------|-----|-----|--------|------|------|------|------|----------|----------|
| OP | 0 | 51.8 | 0 | 0.01 | 0.07 | 3.21 | 0.81 | 8.8 | 94.1 |
| SP | 0 | 116.2 | 0 | 0 | 0 | 1.10 | 10.0 | 103.3 |
| IGR3 | 0 | 484.0 | 0.22 | 0.46 | 1.56 | 32.92 | 6.95 | 11.9 | 168.9 |
| CYR | 0 | 63.8 | 0.05 | 0.07 | 0.63 | 25.87 | 3.47 | 3.7 | 14.1 |
| NEO | 0 | 64.0 | 0 | 0.06 | 0.50 | 13.00 | 2.05 | 5.7 | 45.1 |
| MLI | 0 | 4.0 | 0 | 0 | 0 | 0.04 | 9.7 | 112.9 |

Conclusions

Animal and environmental health, alongside human health, are criteria assessed by the Australian Pesticides and Veterinary Medicines Authority and the New Zealand Ministry for Primary Industries to administer regulatory approval of agricultural compounds and veterinary medicines. Maintaining healthy sheep involves eradicating ectoparasites from the animals. Industry monitoring of ectoparasiticide residues in wool is used to measure the impact of both government and wool industry policies and practices by examining long term residue trends and determining the level of compliance with EU pesticide residue limits. Data analysed from Australia and New Zealand over the last three decades provides evidence that the practice of pest control for sheep has significantly improved through a shift away from older ectoparasiticide technology. Close to 100% of greasy wool harvested from Australia and New Zealand complies with the EU Eco-label limits for ectoparasiticide residues.

NGO organisations involved in benchmarking the environmental credentials of different types of textile fibres reference data and modelling techniques to establish indices which ultimately provide an environmental classification. Independent scientific verification of the data used for such studies provides transparency to consumers. Contemporary wool residue data taken systematically over the last three decades in Australia and New Zealand augments international procedures and regulations which have increased the supply of ‘eco-wool’ compliant fibre. The ectoparasiticide approvals processes in Australia and New Zealand examine human, animal and environmental risks and cover physico-chemical properties, toxicology, phytotoxicity, hazard assessment, product labelling and withholding periods required between animal treatment and shearing.

A standard relating to pesticide residue testing, managed by the International Wool Textile Organisation is available to participating signatory countries for monitoring residues to mitigate and eliminate environmental and human health impacts from the use of animal health treatments. The acquisition of relevant data for modelling and classification of fibre types adds to a credible resource that can be analysed periodically to assess progress with wool residue management. The Australian and New Zealand wool residue monitoring data updates information showing positive downward trends and evidence of cleaner practices.
Figure 2. Time domain trends for greasy wool ectoparasiticide residue levels with EU limits (a) OP, (b) SP, (c) IGR3.
Figure 3. Time domain trends for greasy wool ectoparasiticide residues with no EU limits, (a) CYR, (b) NEO, (c) MLI, (d) SPI.

Table 4. Regression model summary statistics for the mean and median residue levels.

| Active | Mean residue concentration | Median concentration |
|--------|----------------------------|----------------------|
|        |                            |                      |
|        | Australia                  | Australian + NZ      |
|        | Pseudo R² (%) RSE (ppm)    | Pseudo R² (%) RSE (ppm) |
| OP     | 90.4 0.852 86.0            | 1.336                |
| SP     | 87.6 0.725 56.7            | 1.287                |
| IGR3   | 90.9 2.069 70.5            | 2.614                |
| CYR    | 73.6 1.462 57.1            | 1.700                |
| NEO    | 90.9 0.234 70.5            | 0.684                |
|        |                            |                      |
|        | Australian                 |                      |
|        | Pseudo R² (%) RSE (ppm)    |                      |
| OP     | 90.4                        | 0.027                |
| SP     | 87.6                        | 0.005                |
| IGR3   | 90.9                        | 0.059                |
| CYR    | 73.6                        | 0.012                |
| NEO    | 90.9                        | 0.0                  |
|        | EU-Ecolabel limit           |                      |
| OP     | Mean (ppm)                  | 0.5                  |
| SP     |                              | 0.5                  |
| IGR3   |                              | 2.0                  |
| CYR    |                              |                      |
| NEO    |                              |                      |
Table 5. Regression model summary for the mean predicted proportion of wool samples meeting EU-Ecolabel compliance.

| Active | Australian trend | Australian + NZ trend |
|--------|------------------|------------------------|
|        | Pseudo R² (%)   | RSE (ppm)              | Pseudo R² (%)   | RSE (ppm)              |
| OP     | 83.4            | 3.175                  | 84.9            | 2.966                  |
| SP     | 79.0            | 1.452                  | 71.7            | 1.817                  |
| IGR_{3} | 90.3           | 4.455                  | 87.5            | 4.802                  |

Figure 4. Percentage of wool production meeting EU compliance (a) OP, (b) SP, (c) (IGR_{3}) (d) all actives (OP + SP + IGR_{3}).

Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Received: 29 April 2021; Accepted: 30 December 2021
Published online: 14 January 2022
References

1. International Wool Textile Organisation. Market Information (International Wool Textile Organisation, 2018).
2. Beef and Lamb NZ. Compendium of New Zealand Farm Facts (2019). http://www.beeflanzbiz.com (Accessed 5 Feb 2021).
3. Australian Wool Innovation Limited. Australian Wool Production and Forecasting Report (2019). http://www.wool.com (Accessed 5 Feb 2021).
4. Australian Department of Agriculture Water and the Environment. Australian Animal Welfare Standards and Guidelines (2016). https://www.abor.gov.au/animal-welfare/standards-guidelines (Accessed 5 Feb 2021).
5. New Zealand Ministry of Primary Industries. Sheep and Beef Cattle Code of Welfare (2018). https://www.mpi.govt.nz/protection-and-response/animal-welfare/codes-of-welfare/ (Accessed 5 Feb 2021).
6. Australian Government. Agricultural and Veterinary Chemicals (Administration) Act 1992 No 262 (1992). https://www.legislation.gov.au/Details/C2016C01012 (Accessed 5 Feb 2021).
7. New Zealand Government. Agricultural Compounds and Veterinary Medicines Act 1997 No. 87. (1997). http://www.legislation.govt.nz/act/public/1997/0087/latest/DLM4145577.html (Accessed 5 Feb 2021).
8. Wall, R. & Shearer, D. Veterinary Ectoparasitides: Biology, Pathology and Control 2nd edn. (Blackwell, 2001).
9. Bureau of Indian Standards. Indian Standard: Textiles - Test Methods for Wool - Part 1: Determination of Ash (IS 14732:1992) (1992).
10. Republic of Korea Ministry of Environment. Tolerance Limits for Industrial Effluents Discharged into Inland Surface Waters IS 2490 (1981).
11. Republic of Korea Ministry of Environment. Water Quality and Ecosystem Conservation Act No. 12519 (2008).
12. Vietnam Environment Administration. Sewerage Act No. 12466 (2008).
13. Vietnam Environment Administration. National Technical Regulations on the Effluent of Textile Industry QCVN 13-MT: 2015/ BTNMT (2015).
14. China Ministry of Environmental Protection. Integrated Wastewater Discharge Standard GB 8978–1996. (1996).
15. China Ministry of Environmental Protection. Discharge Standards of Water Pollutants for Dyeing and Finishing of Textile Industry GB 4287–2012 + XGI-2015. (2015).
16. United States Code of Federal Regulations. Textile Mills Point Source Category CFR Title 40 Part 410. (2011).
17. United States Code of Federal Regulations. Leather Tanning and Finishing Point Source Category CFR Title 40 Part 425. (2007).
18. Germany Federal Ministry for the Environment Nature Conservation Building and Nuclear Safety. Ordinance on Requirements for the Discharge of Waste Water into Waters (Waste Water Ordinance-AbwV) (2004).
19. Food and Agriculture Organisation of the United Nations. Legislative Decree No 152 of the Code on the Environment (2006).
20. European Union. Regulation (EC) No 66/2010 of the European Parliament on the EU Ecolabel. (2009) https://eur-lex.europa.eu/legal-content/EN/5/FR/?uri=CELEX:32010R0066 (Accessed 5 Feb 2021).
21. Wiedermann, S. G. et al. Application of life cycle assessment to sheep production systems: investigating co-production of wool and meat using case studies from major global producers. Int. J. Life Cycle Assess. 20, 463–476. https://doi.org/10.1016/s11367-015-0849-z (2015).
22. Pierlot, A. Competitive positioning using eco-labelling. (CSIRO, 2011) https://publications.csiro.au/rpr/download?pid=csiro:EP112632&dsid=DS1 (Accessed 5 Feb 2021).
23. Bunch, T. R., Bond, C., Buhl, K. & Sone, D. Spinosad General Fact Sheet (2014) http://npic.orst.edu/factsheets/spinosadgen.html (Accessed 19 Nov 2019).
24. Australian Pesticides and Veterinary Medicines Authority (APVMA). (1993). https://apvma.gov.au/ (Accessed 5 Feb 2021).
25. New Zealand Ministry for Primary Industries Agricultural Compounds and Veterinary Medicines (ACVM) (1997). https://www.mpi.govt.nz/agriculture/agricultural-compounds-vet-medicines/ (Accessed 5 Feb 2021).
26. Savage, G. The Residue Implications of Sheep Ectoparasitides: A Report for the Woolmark Company (The National Registration Authority for Agricultural and Veterinary Chemicals, 1998).
27. Campbell, N. J., Morgan, P. D., Roberts, G. S. & Hanrahan, P. D. Precision of Presale Core Sampling When Used to Monitor Chemical Residues in Wool. Report No. RWG 04 (IWTW Raw Wool Group, 1996).
28. Hanrahan, P. D. & Teasdale, D. Overview of Chemical Use in Wool Production in Australia. Report No. 25 (IWTW Technology and Standards, 1998).
29. Ranford, S. L. & Walls, R. J. A Proficiency Testing Trial Comparing Pesticide Residues on Wool. Report No. STG 03 (IWTW Special Topics Group, 1998).
30. Brightling, A., Williams, S. & Teasdale, D. A Laboratory Proficiency Evaluation Program for Pesticide Residues on Wool (IWTW Chemical Residue Working Group Report, 1998).
31. National Association of Testing Authorities (NATA). Format and content of test methods and procedures for validation and verification of chemical test methods. Report No. Technical Note 17 (1998).
32. National Association of Testing Authorities Australia (NATA). Report No. ISO/IEC 17025 (2000, Version 1) (2000).
33. Australian National Residue Survey. First national residue survey laboratory performance evaluation—grey wool. (1999).
34. Russell, I. M. & Nunn, C. R. Subsampling and Analytical Variability in Residue Analysis of Wool Core Samples. Report No. STG-01 (IWTW Technology and Standards Committee, 2001).
35. Russell, I. M. & Nunn, C. R. Modification to DRAFT TM-59: Number of Subsamples. Report No. STG-02 (IWTW Technology and Standards Committee, 2001).
36. Russell, I. M., Nunn, C. R. & Muller, W. J. Sampling, Subsampling and Analytical Variability in Residue Analysis of Wool Core Samples from Backbone-Treated Sheep. Report No. STG-02 (IWTW Technology and Standards Committee, 2001).
37. International Wool Textile Organisation. IWTW Core Test Regulations (International Wool Textile Organisation, 2011).
38. Nunn, C. R., Russell, I. M. & Williams, S. Residues of Pesticides in Australian Wool 2004–2005: Results from AWI Survey. Report No. RWG-03 (IWTW Technology and Standards Committee, 2005).
39. Australian Wool Innovation Limited. National Wool Residues Surveys 1992 to 2019 (2019).
40. New Zealand Wool Textile Organisation. New Zealand Wool Residues Survey, 2015/16 to 2016/17 (2017).
41. Made-by. https://www.made-by.org/ (Accessed 5 Feb 2021).
42. Rousseuw, P. J. & Hubert, M. Anomaly detection by robust statistics. WIREs Data Mining Knowl. Discov. 8, e1236. https://doi.org/10.1002/widm.1236 (2018).
43. National Association of Testing Authorities (NATA). New statistics for NATAs proficiency testing programs (1996).
44. Willco, L. Procedures for handling high rates of pesticide use (California Environmental Protection Agency, 2016).
45. The R Foundation. R statistical package (2019) http://www.r-project.org (Accessed 5 Feb 2021).
46. Cleveland, W. S., Grosse, E. & Shyu, W. M. Local Regression Models, Chapter 8 (Wadsworth & Brooks/Cole, 1992).
47. Clear, M. H. & Kettle, P. R. Retention of diazinon in wool on romney and drysdale sheep and in hair on goats. N. Z. J. Exp. Agric. 10, 19–21. https://doi.org/10.1080/03015521.1982.10427836 (1982).
48. Statisticshowto. https://www.statisticshowto.com/lowess-smoothing/ (Accessed 5 Feb 2021).
49. Cai, J., Russell, I. M. & Pierlot, A. Developing ‘eco-wool’ compliant supply chains for Australian wool. In 12th International Wool Research Conference, Shanghai, China (2010).
Acknowledgements
The authors acknowledge capability deployed within Australian Wool Innovation, Australian Wool Testing Authority and New Zealand Wool Testing Authority to manage collection and testing of wool samples using internationally accepted procedures. This work was supported by Australian Wool Growers and the Australian Government through Australian Wool Innovation Limited, under project OF-00279.

Author contributions
S.R. interpreted chemical residue trends with reference to regulatory systems and international procedures used in Australia and New Zealand. P.S. set up an interface between co-authors, wool industry managers, regulatory authorities and an international technical advisory group to ensure the manuscript described the background and infrastructure supporting animal welfare and clean wool production. C.v.K. analysed data using internationally accepted procedures to generate a tabular and graphical resource for interpretation and publication.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to S.R.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2022