Endangered Australian top predator is frequently exposed to anticoagulant rodenticides

James M. Pay,⁎ Todd E. Katzner, Clare E. Hawkins, Leon A. Barmuta, William E. Brown, Jason M. Wiersma, Amelia J. Koch, Nick J. Mooney, Elissa Z. Cameron

School of Natural Sciences, University of Tasmania, Hobart, TAS, Australia
US Geological Survey, Forest and Rangeland Ecosystem Science Center, Boise, ID, USA
Department of Primary Industries, Parks, Water and Environment, Hobart, TAS, Australia
Forest Practices Authority, 30 Patrick St, Hobart, TAS, Australia
BirdLife Australia Raptor Group, BirdLife Australia, Carlton, VIC, Australia
School of Biological Sciences, University of Canterbury, CHC, New Zealand

HIGHLIGHTS
• First systematic study of AR exposure in an Australian top predator
• ARs were detected in 74% of 50 eagle carcasses collected between 1996 and 2018.
• AR levels were high in comparison to work on other eagle species.
• AR levels associated with proximity to agriculture and human population density.
• ARs may be causing broad contamination of Australia’s terrestrial food chains.

ABSTRACT

Anticoagulant rodenticides (ARs) used to control mammalian pest populations cause secondary exposure of predatory species throughout much of the world. It is important to understand the drivers of non-target AR exposure patterns as context for assessing long-term effects and developing effective mitigation for these toxicants. In Australia, however, little is known about exposure and effects of ARs on predators. We detected AR residues in 74% of 50 opportunistically collected carcasses of the Tasmanian wedge-tailed eagle (Aquila audax fleayi), an endangered apex predator. In 22% of birds tested, or 31% of those exposed, liver concentrations of second generation ARs (SGARs) were >0.1 mg/kg ww. Eagles were exposed to flocoumafen, a toxicant only available from agricultural suppliers, at an exceptionally high rate (40% of birds tested). Liver SGAR concentrations were positively associated with the proportion of agricultural habitat and human population density in the area around where each eagle died. The high exposure rate in a species not known to regularly prey upon synanthropic rodents supports the hypothesis that apex predators are vulnerable to SGARs. Our results indicate that AR exposure constitutes a previously unrecognized threat to Tasmanian wedge-tailed eagles and highlight the importance of efforts to address non-target AR exposure in Australia.

1. Introduction

Anticoagulant rodenticides (ARs) are used worldwide to control mammalian pest populations. These compounds function by inhibiting
blood clotting mechanisms in vertebrates, resulting in internal hemorrhaging (Rattner et al., 2014). The discovery of resistance to the first-generation ARs (FGARs) led to the development of second-generation ARs (SGARs) in the 1970s (van den Brink et al., 2018). To be lethal, FGARs generally require consecutive intake over several days to accumulate sufficiently high concentrations (Erickson and Urban, 2004). Conversely, SGARs are usually lethal from a single exposure and persist longer in the environment (Erickson and Urban, 2004; van den Brink et al., 2018). The persistence of AR compounds (Horak et al., 2018), the delay in mortality after bait consumption (Lee et al., 2006) and the behavioral changes that occur as a symptom of poisoning (Brakes and Smith, 2005; Mooney, 2017) can make poisoned rodents AR vectors to non-target predatory species.

Detrimental non-target exposure to ARs has been shown in numerous populations of predators in Europe and North America (Christensen et al., 2012; López-Perea et al., 2015; Riley et al., 2007; Shore et al., 2003; Thomas et al., 2017). These effects can be significant, with population-level effects from non-target exposure documented for mammals (Jacquot et al., 2013) and raptors (Thomas et al., 2011). It is thought that species that regularly prey upon small rodents are at higher risk of poisoning, due to the likelihood of consuming AR targeted species (Hindmarch and Elliott, 2018). However, the primary consumption of AR baits by non-target species, as well as the potential for SGARs to move through trophic levels, may lead to wider contamination of terrestrial food chains (Hindmarch and Elliott, 2018; Thomas et al., 2011). If such broadscale contamination is apparent, species at higher trophic levels may be at increased risk of AR exposure (Riley et al., 2007; Thomas et al., 2011).

It is necessary to understand the drivers of patterns in non-target AR exposure in order to assess long-term effects and to develop effective mitigation. There are documented differences in AR exposure of predators between the sexes (Mcdonald et al., 1998) and among age groups (Christensen et al., 2012; Ruiz-Suárez et al., 2016). That said, local anthropogenic factors are likely the most significant drivers of overall risk of non-target exposure. For example, human population density and developed surface area have been linked to the probability and level of AR exposure of numerous predators (Lohr, 2018; Lopez-Perea and Mateo, 2018; Noegeire et al., 2015; Sereiys et al., 2015). Agricultural AR use has also been suggested as the cause of non-target poisoning of predators (Birks, 1998; Fourel et al., 2018; Hindmarch et al., 2017; Hughes et al., 2013), but only a few recent studies have found empirical evidence of this relationship (Coeurdassier et al., 2019; López-Perea et al., 2018; Rial-Berriel et al., 2021; Sainsbury et al., 2018).

AR use is largely unmonitored in Australia and recent work has highlighted the need for the evaluation of its effects on Australasian taxa (Lohr, 2018; Lohn and Davis, 2018). The Tasmanian wedge-tailed eagle (Aquila audax flavei) is a subspecies of wedge-tailed eagle endemic to the Australian island of Tasmania (Commonwealth of Australia, 1999). With the loss of the thylacine (Thylacinus cynocephalus) and recent declines in populations of Tasmanian devils (Sarcophilus harrisii), the wedge-tailed eagle serves a particularly important ecological function as one of the few remaining top predators in Tasmanian ecosystems. The subspecies is listed as endangered (Commonwealth of Australia, 1999; State Government of Tasmania, 1995), with conservation concern based upon a series of threats, including nest failures caused by anthropogenic disturbance, low breeding success rates, habitat loss, collisions with anthropogenic structures, lead poisoning, and illegal persecution (Bell and Mooney, 1998; Mooney and Holdsworth, 1991; Pay et al., 2020; Threatened Species Section, 2006).

ARs are not recognized as a significant threat to the Tasmanian wedge-tailed eagle population, as the species generally avoids areas of high human population density, and rodents represent a very small portion of their diet (Marchant and Higgins, 1993). That said, wedge-tailed eagles show a high sensitivity to pindone (Martin et al., 1994), an AR used to control European rabbit (Oryctolagus cuniculus) populations, a primary prey species of wedge-tailed eagles (Debus et al., 2007; Marchant and Higgins, 1993). Furthermore, if ARs are moving through Tasmania’s food chains, then the high trophic position of the wedge-tailed eagle may increase their susceptibility to exposure to various AR compounds. Finally, because of the long-lived and slow breeding life history strategy of this species, it is likely highly vulnerable to increased mortality rates brought on by toxicants such as ARs.

Our aims in this research were to determine to what extent Tasmanian wedge-tailed eagles are exposed to ARs, and to investigate the factors that influence AR exposure in the population. Specifically, we evaluated (1) liver tissue concentrations of individual ARs known to be used in Tasmania and the total SGAR concentration of each individual eagle; and the relationship between both (2) total liver SGAR concentration and (3) probability of exposure with intrinsic (age and sex) and extrinsic (human population density, agricultural land use, and year of death) factors.

2. Methods

2.1. Study area

This study was conducted on mainland Tasmania, an island state located 240 km south of continental Australia. Tasmania covers an area of 68,150 km², with an estimated human population of 520,830 (Australian Bureau of Statistics, 2018; Fig. 1b). Areas of minimal land use, nature conservation and other protected areas account for 50.3% (34,280 km²) of the Tasmanian land area (DPIPWE, 2015). Agriculture occupies 18,900 km² (27.7% DPIPWE, 2015) mostly in the north and east of the state (Fig. 1c). The Tasmanian agricultural land area is comprised of modified pastures (75.4%), native vegetation pastures (14.5%), irrigated crops (8.8%), and non-irrigated crops (1%; DPIPWE, 2015).

2.2. Sample collection

Eagles were collected as carcasses found opportunistically throughout Tasmania (Fig. 1a) between 1996 and 2018, by government departments, various industries, and volunteers. All carcasses were placed in −20 °C freezer storage by the Department of Primary Industries, Parks, Water and the Environment (DPIPWE, Threatened Species Section, Hobart, Tasmania) and the Tasmanian Museum and Art Gallery (TMA, Collection and Research Facility, Rosny, Tasmania). Data recorded for each carcass included location and the date the carcass was found. We thawed the carcasses and harvested tissues from them between May 2017 and March 2018. We collected a whole liver lobe and a muscle sample from each carcass. The tissue samples were stored at −20 °C until sample preparation, when we thawed them at room temperature. We weighed out a 4 g (± 0.1 g) wet weight sample from the middle of each liver lobe using a digital balance (precision ± 0.0001 g (Mettler Toledo, US). New scalpel blades and gloves were used between samples during collection and preparation to prevent cross contamination.

2.3. Residue analysis

2.3.1. Sample preparation

All toxicological analyses were carried out at Edith Cowan University Analytical Facility (Joondalup, Western Australia). Each liver sample was freeze-dried and homogenized. Homogenized samples were transferred into centrifuge plastic tubes (15 ml) and 10 ml of acetonitrile was added to the tubes with a 10 μl (10 ng/μl) solution containing deuterated surrogates. Analytes were extracted using a sonication bath (15 min sonication for each aliquot). After extraction, samples were centrifuged at 3247 relative centrifugal force (rcf) for 5 min, transferred to a new centrifuge tube with 2 ml of hexane, vortexed for 5 min and centrifuged at 3247 rcf for a further 5 min. Each sample was then evaporated and reconstituted in 400 μl of 50:50 ACN/H2O solution. The final
extracts were transferred to 2 ml Teflon-lined vials and stored at 0–4 °C until analysis.

2.3.2 LC-MS analysis

Liver samples were analyzed for ARs registered for use in Australia (Australian Pesticides and Veterinary Medicines Authority, 2019). Concentrations of five SGARs (brodifacoum, bromadiolone, difethialone, difenacoum and flucoumafen) and three FGARs (coumatetralyl, pindone and warfarin) (see Appendix Table A.1 for the manufacturers of the analytical standards and surrogates) were evaluated using a TSQ Quantiva triple quadrupole Mass Spectrometer (LC-MS) from Thermo Fisher (Thermo Fisher Scientific Corporation, US) (see Appendix B for details of the chromatographic method). Calibration curves and recovery rates for each analytical run were calculated using organic chicken livers spiked with three working solutions of each analytical standard. Recovery rates for the target ARs averaged 96.75%, whilst limits of detection (LOD) and limits of quantification (LOQ) ranged from 0.0005–0.0125 mg/kg and 0.001–0.025 mg/kg respectively (Appendix Table A.2). All detections that were >LOD but <LOQ were reported as present at trace levels. Three organic chicken liver blanks were included in each run to monitor cross-contamination. Every 10th sample was reinjected for a duplicate read (average percentage relative standard deviation of recoveries (RSD) 4.1%) and duplicate blind sample extractions were carried out for five randomly selected samples (average RSD 4.1%). Concentrations were reported on a dry weight basis (mg/kg dw).

2.4. Potential drivers of AR exposure

We evaluated potential drivers of AR exposure as a response to a suite of intrinsic and extrinsic explanatory variables. The intrinsic variables we considered were the sex of the bird (determined genetically using muscle tissue; Appendix C) and its age (broadly characterized into adults and pre-adults based on plumage; Appendix D). Extrinsic explanatory variables were the year in which the carcass was found, and both the mean human population density per km² (Australian Bureau of Statistics, 2018) and the proportion of agricultural area (DPIPWE, 2015) in the area surrounding where each carcass was found. Areas we categorized as agricultural included all types of animal production (intensive animal production, native vegetation grazing, and modified pastures grazing) and all types of horticulture (both non-irrigated, and irrigated cropping; see Appendix E). We defined the area around where each carcass was found based on the size of the estimated home range of adult and pre-adult eagles (25 km² for adults and 420 km² for pre-adults; see Appendix F). We buffered each carcass location by an area corresponding to the age-specific home range and calculated the mean human population density per km² and the proportion of agricultural land within the buffered area. To maximize accuracy in estimates of spatial predictor variables, both human population density and agricultural land use area were calculated from data as close to the year the carcass was found as possible (maximum differences between year of death and spatial data were six years for human population and five years for agricultural land use).
2.5. Data analysis

We performed all statistical analyses in R, version 3.2.0 (R Core Team, 2016). We analyzed the data using censored data techniques (R packages NADA; Lee, 2017, and Survival; Therneau, 2018) as some AR concentrations were below the LOD of the LC-MS.

2.5.1. Individual AR and total SGAR concentration

We used a Kaplan-Meier cumulative probability distribution (NADA function ‘cenfit’) to calculate censored summary statistics (mean, median and standard error) of each AR compound and the total SGAR concentration for each individual eagle. We also calculated analogous standard (non-censored) summary statistics for only the eagles in which ARs were detected. Creating these analogous summary statistics facilitated comparisons among our study and prior work as other studies have used this approach (e.g. Hughes et al., 2013; Lopez-Perea and Mateo, 2018). To facilitate comparisons to other studies, we calculated summary statistics on a wet weight basis. To do this we converted dry weight concentrations (provided in mg/kg dw) to wet weight (mg/kg ww) by multiplying the dry weight concentrations by the dry to wet weight ratios of each sample.

We used total SGAR concentrations to estimate the effects of over-all SGAR contamination due to their similar mode of action (Rattner and Harvey, 2021). FGARs were not included in the summed concentrations due to large differences in molecular weight, potency and half-life compared to SGARs (Rattner and Harvey, 2021). To estimate potential toxicological effects of the total SGAR concentrations detected, we used published contamination thresholds (see Lohr, 2018) as follows: (i) 0.001–0.01 mg/kg ww, probably no toxicity; (ii) 0.01–0.1 mg/kg ww, unlikely lethal/possible toxicity; (iii) 0.1–0.5 mg/kg ww, possibly lethal/likely toxicity; (iv) 0.5–0.7 mg/kg ww, probably lethal; (v) >0.7 mg/kg ww, lethal. We used the converted wet weight concentrations for this evaluation as the thresholds were based on wet weight concentrations.

2.5.2. Correlates of degree and likelihood of exposure

We explored relationships between the extrinsic and intrinsic explanatory variables (age, sex, year of death, human population density, and proportion of agricultural area) and total SGAR concentration with left-censored regression models (Helsel, 2012; Survival function ‘survreg’). We assigned censored data the corresponding LOD value to calculate censored summary statistics (mean, median and standard error) of the top-performing model and considered a parameter to be significant if the coefficient of the top-performing model and considered a parameter to have strong support if it was included in all candidate models.

We also explored the relationship between the same suite of extrinsic and intrinsic predictor variables with the probability of AR residues (both of SGARs and FGARs) being detected using a binomial generalized linear model with logit link function. The dependent variable in these models was whether the eagles were exposed (AR concentrations > LOD) or unexposed (AR concentrations < LOD). We again considered all possible parameter combinations and retained models in the candidate set that were both within six Δ AICc and had AICc values smaller than all the simpler models within which they were nested.

3. Results

We analyzed tissue from 50 eagle carcasses that were collected between 1996 and 2018, although most were collected after 2006 (n = 37). All birds were successfully sexed and aged, with 41 eagles identified as pre-adult, and 22 as female. Data available for the sampled carcasses included location (n = 50; Fig. 1a) and year the carcass was found (n = 50).

### Table 1
Summary statistics describing liver AR concentrations of each AR assessed and total liver SGAR concentration of Tasmanian wedge-tailed eagle carcasses collected between 1996 and 2018. Non-censored and censored summary statistics are presented. Non-censored statistics were calculated using only the eagles with detected AR concentrations. Censored summary statistics consider all individuals and account for unknown values below the corresponding limit of quantification (LOQ). All summary statistics are reported on a wet weight basis.

<table>
<thead>
<tr>
<th>AR</th>
<th>Brodifacoum</th>
<th>Bromadiolone</th>
<th>Coumatetralyl</th>
<th>Difenacoum</th>
<th>Difethialone</th>
<th>Flocoumafen</th>
<th>Pindone</th>
<th>Warfarin</th>
<th>Total SGAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOQ</td>
<td>0.005</td>
<td>0.001</td>
<td>0.002</td>
<td>0.0026</td>
<td>0.010</td>
<td>0.0025</td>
<td>0.025</td>
<td>0.002</td>
<td>NA</td>
</tr>
<tr>
<td>Birds exposed (%)</td>
<td>28/50 (56%)</td>
<td>11/50 (22%)</td>
<td>1/50 (2%)</td>
<td>0/50 (0%)</td>
<td>0/50 (0%)</td>
<td>20/50 (40%)</td>
<td>5/50 (10%)</td>
<td>35/50 (70%)</td>
<td>73/50 (74%)</td>
</tr>
<tr>
<td>Max (mg/kg ww)</td>
<td>0.635</td>
<td>0.241</td>
<td>0.014</td>
<td>0.000</td>
<td>0.000</td>
<td>0.348</td>
<td>0.000</td>
<td>0.000</td>
<td>0.651</td>
</tr>
<tr>
<td>Min (mg/kg ww)</td>
<td>0.003*</td>
<td>0.003</td>
<td>0.014*</td>
<td>0.000</td>
<td>0.000</td>
<td>0.002*</td>
<td>0.000</td>
<td>0.001*</td>
<td>0.002</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Not censored</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (mg/kg ww)</td>
</tr>
<tr>
<td>Median (mg/kg ww)</td>
</tr>
<tr>
<td>SE (mg/kg ww)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Censored</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (mg/kg ww)</td>
</tr>
<tr>
<td>Median (mg/kg ww)</td>
</tr>
<tr>
<td>SE (mg/kg ww)</td>
</tr>
</tbody>
</table>

* Trace value.
flocoumafen). Warfarin was detected at very low concentrations (<0.01 mg/kg ww) in two birds and coumatetralyl was detected in one bird.

We recorded potentially lethal total liver SGAR concentrations (≥0.1 mg/kg ww; Newton et al., 1999) in 11 of the wedge-tailed eagles sampled (22%; 31% of those in which SGARs were detected; Fig. 2). Furthermore, concentrations were above probably lethal levels of >0.5 mg/kg ww in 4% of the eagles (6% of those in which SGARs were detected). That said, liver AR concentrations do not allow the confirmation of lethality without a necropsy to identify signs of toxicity.

3.2. Correlates of degree of exposure

The top-performing censored regression model suggested that total liver SGAR concentration (mg/kg dw) was driven most strongly by the year the carcass was found, the amount of agricultural area, and the human population density in the area around where the carcass was found (see Appendix Table G.1). This model was 42.83 times more likely than the null model. A simpler model that excluded human population density was also retained in the candidate model set (Table 2). The year the carcass was found and agricultural area were included in both candidate models, suggesting that these variables were the most important to explaining total liver AR concentration. Coefficients of the best performing model indicated that year of death, agricultural area, and human population density were all positively associated with total AR concentration (Table 3, Fig. 3a). The model suggested that a 10% increase in agricultural habitat in the area around where the bird died would result in an increase in liver AR concentrations by a factor of 4.17. Likewise, each later year in the study was estimated to increase AR concentrations by a factor of 1.17. The relationship between total AR concentration and human population density suggested an increase in 100 habitants per km² would increase total AR concentration by a factor of 7.23.

3.3. Correlates of likelihood of exposure

The top-performing binomial model to explain the probability of an eagle being exposed to ARs included the year the carcass was found and the proportion of agricultural area within the area around where the carcass was found (see Appendix Table G.2). The candidate model set included two simpler models, including the null model (Table 2), although the top-performing model was 8.9 times more likely than the null model based on AICc weight. Coefficients of the top-performing model indicated that the probability of ARs being detected increased with carcasses found more recently and in areas with higher proportions of agricultural area (Table 3). The odds of ARs being detected in a carcass were 1.46 times greater for each 10% increase in agricultural habitat proportion in the area around where the bird died and 1.21 times greater for each advancing year of the study period (Fig. 3b, Appendix Fig. G.1).

4. Discussion

The frequency and magnitude of AR exposure in Tasmanian wedge-tailed eagles, and their correlation to agricultural areas and human population density, have several implications for our understanding of rodenticide exposure and the Tasmanian ecosystem. First, rodenticide exposure is high among these birds, suggesting that rodenticides are frequently finding their way into top predators in the ecosystem. Furthermore, extrinsic (i.e. agricultural area, human population density, and year of death) rather than intrinsic factors (i.e. age, sex) influence the probability of exposure to ARs and total SGAR concentration. These findings illustrate how AR exposure of the Tasmanian wedge-tailed eagle is driven by anthropogenic processes and thus identify directions to solve this conservation problem.

4.1. Individual AR and total SGAR concentration

The high prevalence of SGARs detected in our study is consistent with research implicating SGARs as the predominant cause of non-
target AR exposure of predators (Lohr, 2018; López-Perea et al., 2015). SGARs brodifacoum, bromadiolone, and flocoumafen accounted for 99.6% of the total AR concentrations observed in the Tasmanian wedge-tailed eagle. The first two of these are the AR compounds most commonly identified in non-target predators in numerous ecosystems worldwide (Hosea, 2000; Koivisto et al., 2016; Langford et al., 2013; Ruiz-Suárez et al., 2014; Sharp et al., 2005). Langford et al. (2013) found that agricultural area accounted for only 0.4% of the total AR concentrations observed in the Tasmanian wedge-tailed eagle, suggesting that agricultural asset protection and professional pest controllers could be important sources of non-target AR exposure in Australia.

Table 3
Model coefficients for top performing models describing the estimated effect of each variable on total liver SGAR concentrations (censored regression) and the probability of an individual (0.635 mg/kg ww) is substantially higher than that found in congeners (0.143 mg/kg ww) (Christensen et al., 2012; López-Perea et al., 2015; Walker et al., 2011). The proportion of birds we observed with concentrations >0.2 mg/kg ww (16%) is substantially higher than that found in congeners (0–6%; Hosea, 2000; Langford et al., 2013; Sánchez-Barbudo et al., 2012), and the highest concentration of an SGAR we detected in an individual (0.635 mg/kg ww of brodifacoum) is substantially higher than the highest concentration of an AR previously reported in an Aquila species (0.154 mg/kg ww of bromadiolone; Langford et al., 2013). Both the censored mean SGAR concentrations of all eagles sampled (0.100 mg/kg ww) and the mean only of those with detected SGAR levels (0.143 mg/kg ww) were higher than mean concentrations reported for congeners (0.006–0.073 mg/kg ww; Langford et al., 2013; Sánchez-Barbudo et al., 2012), but lie within the range of values reported for other raptors exposed to SGARs (0.005–0.413 mg/kg ww; Thomas et al., 2011; Christensen et al., 2012; Lohr, 2018).

The high exposure to SGARs in the Tasmanian wedge-tailed eagle, a species not known to regularly prey upon synanthropic rodents, supports the suggestion that apex predators are vulnerable to SGARs (López-Perea et al., 2015; Riley et al., 2007). The long half-life and persistence of SGARs gives these compounds the capacity to move through food chains (López-Perea et al., 2015), a theory evidenced by the presence of ARs in apex predators (Riley et al., 2007). The wedge-tailed eagle preys upon several carnivorous species that are known to consume synanthropic rodents. For example predatory and scavenging species such as forest ravens (Corvus tasmanicus), kookaburras (Dacelo novaeguineae), common brush-tail possums (Trichosurus vulpecula), cats (Felis catus), and other raptors have been recorded in wedge-tailed eagle diets (Marchant and Higgins, 1993). The potential for SGARs to move through multiple trophic levels may therefore be causing extensive contamination of Tasmania’s terrestrial food chains (Thomas et al., 2011). If this is the case, then numerous other predatory species may be at risk in the region, including the endangered Tasmanian devil and eastern quoll (Dasyurus viverrinus; IUCN, 2020).

The high exposure we detected may also be driven by the improper use of ARs and non-target AR vectors. The use of SGARs in Australia does not require a license, products can be easily purchased in large quantities, and awareness of use guidelines may be low. If SGARs are not being used as directed, numerous non-rodent species may consume the poisons and act as AR vectors to predators. Furthermore, ARs have recently been detected in Australian reptile species; this exposure could be through direct consumption of ARs used correctly, since these species are small enough to enter AR bait boxes (Lettoof et al., 2020). Reptiles are prey for wedge-tailed eagles, as well as other predators, and may therefore have a role as AR vectors in Australia.

Fig. 3. a) Predicted response of total liver SGAR concentrations (mg/kg dw) in Tasmanian wedge-tailed eagle carcasses as a function of the proportion of agricultural land area and mean human population density in the area around where the bird died. The three lines are the estimated response of liver AR concentration with human population per km² held at three levels. Year of carcass discovery is held at its mean. b) Logistic plot of the effect of year of death on the probability of AR exposure. Agricultural land area is held at its mean.
4.2. Correlates of AR exposure

The positive association between hepatic AR concentrations and human population density and agricultural land use may indicate localized use that is having wider scale effects. AR residues in predators have been linked to human population density (López-Perea et al., 2018, 2015), the amount of urbanized area (Coeurdassier et al., 2019; Lohr, 2018; Seriesy et al., 2015), and the amount of both arable and pastoral agriculture (Coeurdassier et al., 2019; López-Perea et al., 2018; Sainsbury et al., 2018). These relationships are unsurprising in study species known to use urban and agricultural habitats. However, Tasmanian wedge-tailed eagles are less associated with densely populated areas. Although human population growth has been relatively low in Tasmania for the past two decades, there has been an increase in the number of residences built in more rural and natural areas and agricultural development has expanded (Australian Bureau of Statistics, 2018). Such practices may introduce ARs into more natural areas. Furthermore, if ARs are passing through multiple trophic levels, they will spread more widely from the initial bait. The effects of these more remote developments and agricultural activities may therefore have incommensurately greater effects on predatory species than suggested by the landscape footprint.

4.3. Recent increases in AR exposure

The higher total SGAR concentrations and probability of AR exposure of the birds that had died more recently could be due to either the increased exposure to ARs over time or the degradation of the compounds with prolonged storage. Although SGAR residues are stable within tissues over the short-term (Gallocchio et al., 2014; Jin and Chen, 2006), the effects of long-term − 20 °C freezer storage on tissue residues is not well understood, with studies documenting various rates of degradation (e.g. 6–41% over 0.5–3 years; P. Fisher unpublished data; Vindenes et al., 2008). Despite this, patterns in the AR concentrations we detected are consistent with increased probability of exposure over time. There would need to be a substantial reduction in AR residues (much greater than the degradation rates documented) for an AR-exposed bird to be considered unexposed in our study, as the lowest AR concentration we detected was still 200% greater than the associated LOD. Consequently, the increased AR concentrations in Tasmanian wedge-tailed eagles that had died more recently is more likely due to increases or changes in AR use in Tasmania than to sample degradation. However, there is no information available on the volume of ARs used in Australia (Lohr and Davis, 2018), which impedes our quantification of the relationship between AR application and non-target AR exposure.

4.4. Conservation implications

Our results indicate that AR exposure is likely a significant factor to consider in the conservation management for the Tasmanian wedge-tailed eagle. This is true even given the potential biases inherent to the non-random carcass collection we relied on to gather samples. AR studies using opportunistic samples may inflate the proportion of animals with sub-lethal AR concentrations detected and underestimate the proportion of birds detected with fatal levels (Lohr, 2018; Newton et al., 1990). We found exposure at rates that are high compared to other studies using similar sampling methods.

The use of AR concentration thresholds to interpret the likely physiological result has limitations due to inter- and intra-specific variation in susceptibility to toxicity (Rattner and Harvey, 2021; Thomas et al., 2011). That said, concentrations in 22% of the birds we studied were well above the potentially lethal range reported for European barn owls (Tyto alba; >0.1 mg/kg; Newton et al., 1999). Furthermore, 56% had levels that can cause symptoms of toxicity in other species (>0.01 mg/kg; Lohr, 2018; Murray, 2018). These comparative data therefore suggest that the level of exposure we detected indicates that AR exposure could be influential to survival and possibly conservation of these birds.

Our findings underscore the importance of efforts to address non-target AR exposure in Australian wildlife. SGARs are currently registered for domestic (non-professional) use in Australia (Australian Pesticides and Veterinary Medicines Authority, 2019), despite increasing regulation and monitoring in other countries (USEPA, 2008). Increased legislative control of SGARs and removal from public retail have been suggested as steps to reduce the ecological effects of SGAR use in Australia (Lohr and Davis, 2018). However, our findings of an association between agriculture and AR concentrations in the Tasmanian wedge-tailed eagle, as well as widespread contamination of an AR not readily available for residential use (floucaufen), suggests that professional pest control may also be an important cause of non-target AR exposure. Addressing mechanisms of spread from both professional and non-professional application of SGARs may therefore be important to reducing AR exposure in Tasmanian wedge-tailed eagles and other Australian wildlife.

Disclaimer

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

Data accessibility

Data available as electronic supplementary material.

Funding

This work was supported by Woolnorth Wind Farms, TasNetworks, New Forests, Norske Skog, and the Holsworth Wildlife Research Endowment.

CRediT authorship contribution statement

James M. Pay: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Project administration, Funding acquisition, Writing – review & editing. Todd E. Katzner: Conceptualization, Methodology, Investigation, Writing – original draft, Supervision, Formal analysis, Writing – review & editing. Clare E. Hawkins: Conceptualization, Writing – original draft, Supervision. Leon A. Barmuta: Formal analysis, Writing – review & editing. William E. Brown: Investigation, Resources, Writing – review & editing. Jason M. Wiersma: Conceptualization, Investigation, Writing – review & editing. Amelia J. Koch: Conceptualization, Writing – original draft, Supervision, Funding acquisition. Nick J. Mooney: Investigation, Resources, Writing – review & editing. Elissa Z. Cameron: Conceptualization, Writing – original draft, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was possible due to the long-term storage of Tasmanian wedge-tailed eagle carcasses provided by the Tasmanian Museum and Art Gallery and the Department of Primary Industries, Parks, Water and Environment. We thank the numerous people and organizations that were involved in collecting these carcasses. B. Bauer, J. Harris, and N. Dannemiller assisted necropsies. We also thank Mike Lohr, Francesco Busetti, and Kirstin Proft for their contribution to this
research. Laboratory analyses were carried out by Edith Cowan University Analytical Facility.

Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147673.

References


Australian Pesticides and Veterinary Medicines Authority, 2019. Public chemical registration information system search. (Canberra).


