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Long-term trends of second generation anticoagulant rodenticides (SGARs) show widespread contamination of a bird-eating predator, the Eurasian Sparrowhawk (*Accipiter nisus*) in Britain☆

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ABSTRACT

Second generation anticoagulant rodenticides (SGARs) are widely used to control rodents around the world. However, contamination by SGARs is detectable in many non-target species, particularly carnivorous mammals or birds-of-prey that hunt or scavenge on poisoned rodents. The SGAR trophic transfer pathway via rodents and their predators/scavengers appears widespread, but little is known of other pathways of SGAR contamination in non-target wildlife. This is despite the detection of SGARs in predators that do not eat rodents, such as specialist bird-eating hawks. We used a Bayesian modelling framework to examine the extent and spatio-temporal trends of SGAR contamination in the livers of 259 Eurasian Sparrowhawks, a specialist bird-eating raptor, in regions of Britain during 1995–2015. SGARs, predominantly difenacoum, were detected in 81% of birds, with highest concentrations in males and adults. SGAR concentrations in birds were lowest in Scotland and higher or increasing in other regions of Britain, which had a greater arable or urban land cover where SGARs may be widely deployed for rodent control. However, there was no overall trend for Britain, and 97% of SGAR residues in Eurasian Sparrowhawks were below 100 ng/g (wet weight), which is a potential threshold for lethal effects. The results have potential implications for the population decline of Eurasian Sparrowhawks in Britain. Fundamentally, the results indicate an extensive and persistent contamination of the avian trophic transfer pathway on a national scale, where bird-eating raptors and, by extension, their prey appear to be widely exposed to SGARs. Consequently, these findings have implications for wildlife contamination worldwide, wherever these common rodenticides are deployed, as widespread exposure of non-target species can apparently occur via multiple trophic transfer pathways involving birds as well as rodents.

1. Introduction

Small rodents cause widespread conflict with human interests throughout the world, particularly commensal species such as House Mice (*Mus musculus*) and Brown Rats (*Rattus norvegicus*) (Lund, 2015). Rodenticides are widely deployed worldwide to control rodent populations in order to reduce the risk of disease transmission to people and livestock, and to limit costly damage to crops, food stores, infrastructure and forestry through gnawing and spoilage (Meyer and Kaukeinen, 2015; Shore, 2018). There has also been widespread use of rodenticides to eradicate invasive rodents from island ecosystems, where their predation of eggs and chicks threatens seabird colonies (Howald et al., 2015).

Rodenticides are typically deployed in bait that is consumed by the target species, but many populations of rodents have developed a resistance to first generation anticoagulant rodenticides, such as warfarin (Pelz and Prescott, 2015; Berny et al., 2018). Consequently, these compounds have largely been replaced by second generation

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anticoagulant rodenticides (SGARs), which have a higher toxicity and interrupt the rodent's blood clotting by inhibiting the vitamin K epoxide reductase (Shore, 2018).

Despite the economic, public health and some ecological advantages of SGARs, there are substantial concerns over exposure of non-target species around the world, such as other mammals and birds that can also encounter the baits (Shore et al., 2015; Van den Brink et al., 2018). In addition to the widespread primary exposure of non-target wildlife to SGARs (Elliott et al., 2014; Shore and Coeurdassier, 2018), secondary exposure can also cascade through trophic levels to the predators and scavengers that feed upon contaminated prey (López-Perea and Mateo, 2018). In Britain, for example, Roos et al. (2021) found that population declines of rodent-eating Common Kestrels (*Falco tinnunculus*) were negatively correlated with concentrations of SGARs in their livers. However, despite secondary contamination and poisoning by SGARs being a known environmental risk, for most non-target species it is unclear what ecological significance this exposure poses for individuals and populations (Rattner et al., 2014).

Because of the global use of SGARs to control rodents, the variety of non-target species that can potentially be exposed is very large. There are numerous studies worldwide documenting secondary exposure of non-target wildlife to SGARs (e.g. Elliott et al., 2014, 2016; Geduhn et al., 2015; Justice-Allen and Loyd, 2017; Thomas et al., 2017; Vyas, 2017; Shore et al., 2018; López-Perea and Mateo, 2018; Elmeros et al., 2018; Sainsbury et al., 2018). However, studies of SGAR contamination in predatory birds have overwhelmingly focused on species that mostly feed or scavenge on target and non-target rodents, reflecting the obvious expected transfer pathway via animals that have consumed SGAR bait (Geduhn et al., 2016; Huang et al., 2016; Salim et al., 2014; Herring et al., 2017; Walker et al., 2017; Rattner and Harvey, 2021). Increasingly, there is recognition that other trophic pathways of exposure may exist, and for many predatory birds and mammals the precise transfer pathways for risk of exposure remain poorly understood (Rattner et al., 2014; Hindmarch and Elliott, 2018).

In addition to species that feed on rodents, there is increasing evidence from Europe and North America that specialist bird-eating predators, such as raptorial falcons (*Falco* spp.) and hawks (*Accipiter* spp.), are also being exposed to SGARs, which would involve an unexpected trophic transfer pathway of rodenticides widely entering avian food chains (Thomas et al., 2011; Hughes et al., 2013). These raptors commonly prey upon small songbirds, and previous work (Walther et al., 2021) has demonstrated that 28% of songbirds around farms in Germany carried residues of SGAR from local bait stations. These songbirds appear to enter the plastic boxes used to deploy baits, which they probably fed upon, and may also face secondary exposure by eating contaminated invertebrates (Vyas, 2017; Shore and Coeurdassier, 2018; Walther et al., 2021). Despite the potential importance of this pathway in contaminating bird-eating raptors with SGARs, there is little information to establish if it is widespread in natural systems.

In Britain, Hughes et al. (2013) and Walker et al. (2015) examined Eurasian Sparrowhawks (*Accipiter nisus*; hereafter 'Sparrowhawks'), a specialist bird-predator, to assess the proportion of individuals that contained detectable SGAR concentrations in their livers. The results showed that the proportion of contaminated Sparrowhawks was similar to that found in other avian predators that mainly eat rodents, although the SGAR concentrations in Sparrowhawk livers were generally lower than in the rodent-predators. As Sparrowhawks prey almost exclusively upon small to medium-sized birds, such as songbirds and pigeons (Newton, 1986), this evidence suggests that exposure of predators to SGAR through avian pathways is occurring (Walther et al., 2021), and may be as widespread and important as the widely recognised rodent pathways (Brakes and Smoth, 2005).

The UK population trend for Sparrowhawks has fluctuated during the 20th Century in response to exposure to environmental pollutants, such as organochlorine pesticides, but a more recent decline in abundance over the past 15 years remains unexplained (Newton, 1986; Woodward et al., 2020). As such, understanding the extent and risk of SGAR exposure for Sparrowhawks may be important at the population level, and can enable better targeting of mitigation measures for reducing SGAR exposure, such as limiting access to bait by prey species (Walther et al., 2021).

Studies of bird-eating raptors, such as Sparrowhawks, have so far involved relatively small sample sizes (fewer than 95 birds) over restricted timespans or spatial extents that provide only a limited picture of secondary exposure (e.g. Thomas et al., 2011; Hughes et al., 2013; Langford et al., 2013; Walker et al., 2015). Analyses based on long-term sample collection and large-scale datasets offer the greatest potential in detecting spatio-temporal trends in SGAR exposure (Walker et al., 2008a). Incorporating variables of age and sex can add further value to such studies, by accounting for different life histories, levels of exposure and accumulation of SGAR residues among individuals (Walker et al., 2015; Shore et al., 2015; Roos et al., 2021).

In this study, we use a unique long-term dataset to examine the trend of rodenticide contamination in the bird-eating Sparrowhawk, collected over twenty years from across Britain. We assess the spatio-temporal variation in liver SGAR concentrations by age and sex of the birds, to test for possible differences in exposure and accumulation with age. We also compare trends in British regions of differing human population density and agricultural activity, this being predominantly arable or grazing land cover.

This study aimed to test the following hypotheses: firstly, that the prevalence of SGAR residues in Sparrowhawks has increased over time. Secondly, that liver concentrations are greater in adults than in juveniles, due to accumulation over a longer lifespan. Thirdly, that birds recovered from regions dominated by arable agriculture and urbanisation will have the highest SGAR contaminations. Finally, that female Sparrowhawks, which feed on larger birds, will have greater SGAR concentrations than males.

The results are important for understanding the extent of SGAR contamination in the avian trophic transfer pathway at an unprecedented large (national) scale and long duration (two decades). Furthermore, the results have potentially global implications for wherever these rodenticides are deployed, by indicating the extent to which additional pathways of wildlife exposure may exist, independent of the rodent pathway.

2. Material and methods

2.1. Bird sampling

The study period was defined as 1995–2015, by which time the Sparrowhawk population in Britain had recovered from the catastrophic effects of organochlorine pesticides that had eliminated the species from much of its range during the 1950–1980s (Newton and Wyllie, 1992; Walker and Newton, 1998).

A total of 259 dead Sparrowhawks were available, having been found and submitted by the public to the Predatory Bird Monitoring Scheme (PBMS). The PBMS is an umbrella project that includes the UK Centre for Ecology & Hydrology's long-term contaminant monitoring and surveillance of avian predators (Shore et al., 2005). Bird carcasses were sexed, and aged as adults or juveniles, based on plumage and morphology (Baker, 2016). Samples comprised 134 adults and 125 juveniles (146 females and 113 males). Juveniles were birds hatched in the current or previous calendar year prior to dying, and adults were birds in their third calendar year or older. A post-mortem examination identified the putative cause of death from the physical condition of the bird and circumstances of its finding, such as road traffic collisions or starvation.

2.2. SGAR analysis

Liver tissues from the birds were archived at −20 °C by the PBMS for long-term storage and future analysis (Shore et al., 2005). We analysed liver tissues for five SGARs licensed for use in the UK: brodifacoum, bromadiolone, difenacoum, flocoumafen and difethialone. Approximately 0.25 g of liver was dried and ground with sodium sulphate in a pestle and mortar. Samples were extracted with chloroform: acetone (1:1 v/v) using a mechanical shaker (Stuart SF1, Bibby Scientific) for 1 h, then centrifuged and the supernatant was transferred to a clean tube. This process was repeated twice with clean solvent and the extracts were combined.

The extract was filtered (0.2 mm PTFE filter) and then cleaned using automated size exclusion chromatography (Agilent 1200 HPLC system). The clean extract was evaporated and the residue was re-suspended in chloroform: acetone: acetonitrile (1:1:8 v/v) and was further cleaned using solid phase extraction cartridges (ISOLUTE® SI 500 mg, 6 ml). The final residue was dissolved in 1 ml of LCMS-MS mobile phase.

LCMS-MS analyses were performed using an 'Ultimate 3000' HPLC coupled to a triple quadrupole 'Quantum Ultra TSQ' mass spectrometer (Thermo Fisher Scientific, Hemel Hemsptead, UK) interfaced with an ion max source in Atmospheric Pressure Chemical Ionisation (APCI) mode with negative polarity and operated with Xcalibur software™ (V.2.0.7.).

The SGARs were separated using a programme with different ratios of mobile phase A: 0.77 g/l ammonium acetate in water, and mobile phase B: 0.77 g/l ammonium acetate in methanol at a rate of 0.3 ml min^{-1}. Gradient elution started from 70% A to 30% B, increased to 60% B in 2 min and held until 6 min; it was then ramped to 70% B at 8.5 min and finally to 100% B at 12 min, held for 1 min and then returned to starting conditions.

The rodenticides standards (Dr Ehrenstorfer, LGC Group, Teddington, UK) were matrix matched. The liver samples were run in batches of 12, which incorporated a blank prepared with chicken liver, and a spiked recovery standard prepared with chicken liver. Recoveries of the spiked chicken liver ranged between 68 and 110% for all compounds with mean concentrations of: bromadiolone (82.9%), difenacoum (92.2%), flocoumafen (91.7%), brodifacoum (96.75) and difethialone (87.8%). The limit of detection (LOD) was 2.3 ng/g wet weight for all compounds, except for 3.0 ng/g wet weight for difethialone.

2.3. Regional grouping

Sampled Sparrowhawks were grouped into four geographical regions in Britain, comprising Scotland (58 birds), northern England (46), western England with Wales (65), and eastern England (90) (Fig. 1). These regions differ in the dominant types of agriculture and urbanisation as depicted in the UKCEH Land Cover Map 2007 (Morton et al., 2014), which was generated from classified satellite imagery in the mid period of the data collection for Sparrowhawks (1995–2015).

We calculated the percentage cover for each region of combined urban and suburban land classes to reflect urbanisation, and also separate classes of arable and improved grassland that both reflected intensive agriculture. Scotland had the lowest coverage of urbanisation and intensive agriculture (both arable and grassland), and eastern England had the highest combined coverage of those land uses (particularly arable and urban), with the other regions being intermediate (Supplementary Material S1). These values offered a gradient over which to compare SGAR residues in Sparrowhawks.

These geographical regions also encapsulated the potential dispersal distances of Sparrowhawks within Britain (Newton, 1986), and so the regions attempted to account for the potential differences in SGAR exposure from varying land use that Sparrowhawks would encounter throughout their life.

2.4. Statistical analysis

Our statistical analysis was framed around the four main questions of differences in residue concentration between juveniles and adults, between the sexes, between regions, and assessing the trend in residue

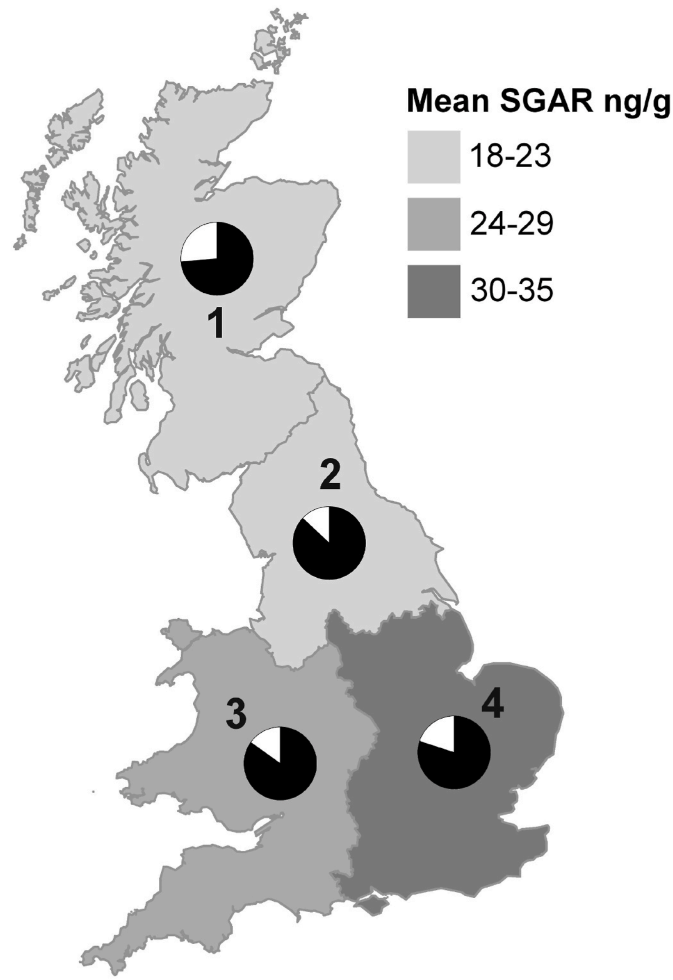

Fig. 1. The mean summed SGAR concentration (above the limit of detection: 2.3 ng/g wet weight) in the livers of 210 Sparrowhawks in four regions of Britain (numbered 1–4). Circle charts within regions show the proportion of birds in each region with summed SGAR concentrations that were above (black) or below (white) the limit of detection. Regions (and Sparrowhawk sample sizes for each) are: 1 = Scotland (58 birds), 2 = Northern England (46 birds), 3 = Western England & Wales (65 birds) and 4 = Eastern England (90 birds).

concentration in Sparrowhawks over time. Summary statistics for age and sex were initially derived for all compounds and summed SGARs, using all birds and values above the LOD. We then modelled concentrations of the three most common residues detected in the birds, which provided sufficient sample sizes for analysis: difenacoum, bromadiolone and brodifacoum.

We modelled each of the three main residue concentrations individually, assuming a log-normal distribution, and used an AR(1), i.e. autoregressive, process to account for residual temporal autocorrelation, where the current value is based on the immediately preceding value. Observations below the LOD were treated as censored, i.e. below the range of accurate measurement. Censored data result in uncertainty around the true value of observations that are below the LOD, and are therefore unobserved, but these records do contain information and can be retained in the analysis if the uncertainty is accounted for.

We used a Bayesian framework as this provides a natural framework for retaining the individual censored residues below the LOD, whilst capturing the uncertainty that arises from the LOD. Where the state of interest cannot be fully observed, as with observations occurring below the LOD, the resulting censored data can be treated as additional parameters from a fully Bayesian perspective, with a likelihood function specifying joint modelling for both observed and censored data (Qi et al., 2022). Within the JAGS program, we used the 'dinterval' distribution function for general interval-censored data (Plummer, 2003) to implement our statistical models. Logged residue data, $Y_{i,t}$, were modelled as either observed (for values above the LOD) or censored (for the values at the LOD), assuming a censored normal distribution, with the log of the censored data assumed to occur within the interval between minus infinity and the log(LOD) (corresponding to the interval from zero to the LOD on the original scale):

$$\log\left(Y_{i,t}\right) \sim \text{normal}\left(\mu_{i,t}, 1/\tau\right)$$

where Y_{it} is the concentration in bird i in year t and τ is an unknown precision parameter.

For each bird i in each year t the model for the expected log concentration μ_{it} was of the form

$$\mu_{i,r,t} = \alpha_0 + \alpha_{r_i} + \beta_{r_i} t + age_i + sex_i + AR1_t$$

This model assumes that log-concentrations depend on effects of age (*age*$_i$, immatures and adults) and sex (*sex*$_i$, males and females), both of which were entered as categorical covariates. It also assume they depend on the region r_i to which the bird belongs, with regional intercepts α_r for each of the four regions and regional trends over time β_r for each region r. Finally, the model contained an AR(1), i.e. autoregressive, process to account for residual temporal autocorrelation, where the current value is based on the immediately preceding value:

$$AR1_t \sim \text{normal}\left(\varphi^* AR1_{t-1}, 1/\tau_{AR},\right)$$

$$AR1_{t=0} \sim \text{normal}\left(\varphi^* \rho, 1/\tau_{AR}\right)$$

$$\rho \sim \text{normal}\left(0, 1/\left(\tau_{AR}^*\left(1-\varphi^2\right)\right)\right)$$

where τ_{AR} is the residual precision for the AR(1) process. The inclusion of the AR(1) process allows for any temporal autocorrelation in the residuals of the linear regression model. If such autocorrelation existed, but was not accounted for in the model, this would be likely to lead to pseudo-replication where the model over-estimates the effective sample size, and so under-estimates uncertainty, which can lead to the detection of spurious relationships.

All priors were set to be diffuse, in order to be as minimally informative as possible:

$$\alpha_0, age_{adult}, sex_{male}, \alpha_r \sim \text{normal}(0, 10000)$$

$$\tau, \tau_{AR} \sim \text{gamma}(0.001, 0.001)$$

$$\varphi \sim \text{uniform}(-1, 1)$$

All models were fitted using R (R Core Team, 2021), JAGS (Plummer, 2003) and the jagsUI package (Kellner, 2017), and marginal posterior distributions of unobserved quantities were approximated using the Markov Chain Monte Carlo (MCMC) algorithm. Three chains of 50,000 iterations were retained after discarding 50,000 iterations as burn-in. Chains were initialised with values diffuse from the mean of the priors. Convergence was assessed by monitoring the trace or trajectories of the posteriors of variances and estimated parameters using the Gelman-Rubin convergence statistic (R′) for each stochastic node (Brooks and Gelman, 1998). Model residuals were tested for any remaining temporal autocorrelation using the 'acf' function in R (Venables and Ripley, 2002).

We derived regional trends, where each regional trend was estimated using the overall proportion of the total national population per region, derived from the mean abundance from breeding bird survey (BBS) data per region per year, $p_{r,t}$:

$$\mu_{i,t} = \left(\alpha_0 + \alpha_{r_i} + \beta_{r_i} t\right) {}^* p_{r,t}$$

We also estimated a slope parameter for a national trend, as the weighted sum of regional slope parameters, β_{r_i}, weighted in proportion to the mean overall proportion of the total national population per region across all years of observation. The BBS data are derived from British Trust for Ornithology long-term monitoring, which provides species abundance data from a national survey network of 1 × 1 km squares chosen by stratified random sampling (Newson et al., 2005). Because residue concentrations were undetected in some birds, it was not feasible to model the summed SGAR residues whilst accounting for the uncertainty associated with the censored observations. Applying a model to only the summed SGAR concentrations does not contain enough information for quantifying the effect of censoring on each individual residue. This is because such a model would not define a distribution for each individual residue to allow for the non-detections to be dealt with in a robust manner.

3. Results

3.1. SGAR concentrations by compound, bird age and sex

Overall, 81.1% of the 259 Sparrowhawks collected in Britain between 1995 and 2015 had at least one SGAR compound in their livers at concentrations above the LOD. A total 42.9% of birds contained residues of two or more SGARs and 12.4% contained three compounds. The most frequently detected SGAR exceeding the LOD was difenacoum (72.2% of birds), followed by bromadiolone (37.5%) and brodifacoum (29.3%). Difethialone was detected in only one bird and flocoumafen was detected in none.

Summary statistics for individual compounds and summed SGARs are given in Table 1. As well as being the most frequent SGAR detected, concentrations of difenacoum also averaged higher than other compounds. Nevertheless, concentrations of difenacoum were mostly below 60 ng/g (Fig. 2). The maximum detected concentration of summed SGARs in an individual bird's liver was 157 ng/g wet weight (Table 1), but 97.3% of all 259 samples were below 100 ng/g. Regional information for summed SGARs is given in Fig. 1, showing higher mean concentrations in southern regions of Britain, and a high proportion of birds containing detectable SGARs in all regions.

Table 1
Summary values for SGAR residue concentrations for Sparrowhawks collected Britain during 1995–2015, grouped by age and sex for each residue compound and the sum SGAR concentration. Values refer only to those above the limit of detection (LOD) of a minimum 2.3 ng/g ww (wet weight).

SGAR ng/g ww	Juvenile n = 125	Adult n = 134	Female n = 146	Male n = 113	All birds n = 259
Difenacoum:					
Mean	12.30	20.52	16.66	17.77	17.18
SD	12.13	22.60	21.26	17.21	19.44
Median	7.83	11.71	9.78	11.71	10.28
Maximum	62.49	150.18	150.18	94.86	150.18
N	76	111	100	87	187
Brodifacoum:					
Mean	6.47	10.12	10.67	7.85	9.11
SD	7.50	13.54	13.12	11.47	12.23
Median	4.55	5.10	5.34	4.59	4.65
Maximum	36.00	68.07	59.16	68.07	68.07
N	21	55	34	42	76
Bromadiolone:					
Mean	16.52	13.60	16.15	13.25	14.95
SD	20.09	14.21	17.13	17.27	17.16
Median	8.70	6.40	8.27	6.06	6.90
Maximum	95.52	59.09	67.20	95.52	95.52
N	45	52	57	40	97
Sum SGAR:					
Mean	20.02	28.09	23.86	25.69	24.67
SD	22.73	28.04	26.25	26.17	26.17
Median	13.92	17.99	15.68	15.82	15.75
Maximum	145.85	157.31	157.31	145.85	157.31
N	89	121	117	93	210

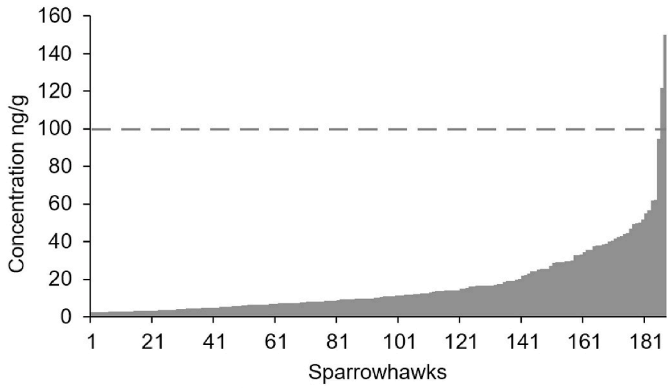

Fig. 2. Histogram of difenacoum concentrations (ng/g wet weight) in the livers of 187 British Sparrowhawks. Concentrations exclude those of 72 birds below the limit of detection (2.3 ng/g). Dashed line at the concentration of 100 ng/g indicates the minimum threshold for potential lethal effects.

3.2. SGAR modelling

The statistical models describing individual SGAR concentrations in Sparrowhawks converged satisfactorily, with all potential scale reduction factors estimated to be less than 1.1 for the two most prevalent compounds, difenacoum and bromadiolone, but the model for brodifacoum reported convergence issues around several parameters. Examination of residuals showed no significant temporal autocorrelation remaining after inclusion of the AR(1) structural process. Given that only difenacoum was detected at a frequency of greater than two-thirds of sampled birds (Table 1), the results hereafter focus on difenacoum as the dominant compound. Modelling results for bromadiolone and brodifacoum are included in Supplementary Material S2.

The modelling of difenacoum showed strong evidence that adults had substantially greater concentrations than juveniles, as predicted, and also that males had higher concentrations than females (Table 2). Difenacoum concentrations varied regionally, showing strong evidence for significantly lower values in Scotland than in northern England or western England with Wales (Table 2). There was some weaker evidence that concentrations in eastern England were also greater than in Scotland.

Difenacoum concentrations in birds from eastern England showed strong evidence for a positive increase over 1995–2015 (Table 2; Fig. 3). There was some support for a similar, but weaker, increasing trend in Scotland, but no strong evidence for any temporal trend in other regions, nor for Britain overall (Table 2).

Table 2
Parameter estimates from Bayesian modelling of difenacoum concentrations in British Sparrowhawks in relation to bird age, sex and geographical region, and regional trends over time. Strength of evidence refers to the proportion of the posterior density for the relevant parameter estimated to be greater or less than zero, depending on the direction of the effect.

Effects:	Estimate	Lower 95% CI	Upper 95% CI	Strength of evidence
Adults > Juveniles	1.052	0.713	1.397	1.00
Males > Females	0.412	0.078	0.749	0.992
Northern England > Scotland	1.036	−0.037	2.127	0.971
Western England & Wales > Scotland	0.972	0.066	1.896	0.982
Eastern England > Scotland	0.531	−0.355	1.423	0.880
Regional trends over 1995–2015:				
Scotland	0.025	−0.033	0.084	0.806
North England	−0.012	−0.076	0.050	0.652
Western England and Wales	−0.00046	−0.053	0.053	0.505
Eastern England	0.043	−0.008	0.095	0.953
National trend (weighted sum of regional trends)	0.013	−0.024	0.049	0.765
Model structural parameters:	Estimate	SD	Lower 95% CI	Upper 95% CI
Intercept	0.228	0.421	−0.590	1.029
Residual process variance ($1/\tau$)	1.545	0.180	1.232	1.934
AR(1) φ	−0.181	0.421	−0.848	0.772
AR(1) $1/\tau_{AR}$	0.076	0.044	0.041	0.197

4. Discussion

The results showed that 81% of the 259 Sparrowhawks collected in Britain contained detectable residues of at least one SGAR compound, and 43% of birds contained residues of two or three SGARs in their livers. The dominant compound detected was difenacoum, but residues of bromadiolone and/or brodifacoum were also detected in many birds (≥29%). Nevertheless, the magnitude and frequency of difenacoum residues meant it was the primary component of sum SGAR concentrations in British Sparrowhawks.

Difenacoum and bromadiolone are the most frequently detected compounds in other predatory birds and mammals in Europe, including in Britain (Dowding et al., 2010; Ruiz-Suárez et al., 2014, 2016; Martínez-Padilla et al., 2017; Koivisto et al., 2018; Sainsbury et al., 2018; Walker et al., 2008b, 2020). Difethialone and flocoumafen were essentially absent from British Sparrowhawks in the current study, which may reflect the relatively low frequency of their use for rodent control, compared to other SGARs (Dawson et al., 2003; Reay et al., 2019).

The proportion of Sparrowhawks with SGAR contamination (81%) was greater than that found in Britain for another small raptor, the Common Kestrel (67%, Roos et al., 2021), and comparable to that found in Barn Owls (*Tyto alba*; 78–94% annually, Walker et al., 2020) and Red Kites (*Milvus milvus*; 82–100% annually, Walker et al., 2019). However, the diet of bird-eating Sparrowhawks differs significantly from these other species, which substantially feed on rodents (Cramp and Simmons, 1980; Cramp, 1985). This suggests that exposure to SGARs across Britain via the avian prey pathway is just as prevalent as the rodent pathway.

Despite the evident widespread exposure of Sparrowhawks to SGARs, their sum concentrations were almost all (97%) below the threshold of 100–200 ng/g that has been used to infer the lower end of a potentially lethal range (derived from Barn Owl data: Newton et al., 1999, 2000; Shore et al., 2001). This suggests that SGAR exposure for Sparrowhawks has predominantly been at sub-lethal levels during the two decades of the study period, up to 2015. However, the lack of knowledge regarding the threshold of toxicity is an important limitation for this and other species, and also the limited understanding of the metabolism or half-life of these compounds in wild birds (Rattner and Harvey, 2021).

There is little information for how sub-lethal concentrations of SGARs affect predatory birds and mammals in general, and sensitivity is likely to be species-specific (Thomas et al., 2011). Salim et al. (2014) found reduced breeding productivity of Barn Owls in relation to higher concentrations of brodifacoum detected in their regurgitated pellets. Martínez-Padilla et al. (2017) also found apparent sub-lethal effects of reduced body weight in nestling Common Kestrels, potentially reducing recruitment to the population. Roos et al. (2021) highlighted the potential role of such sub-lethal effects of SGARs as a factor in the decline of Common Kestrels in Britain.

For Sparrowhawks, there is no specific information on the sub-lethal effects of SGARs. However, our results for the concentration of difenacoum in Sparrowhawks showing an increase in eastern England coincides with a declining population and breeding productivity in Britain over a similar period (Woodward et al., 2020). Sainsbury et al. (2018) reported a 1.7-fold increase in SGAR detections in European Polecats

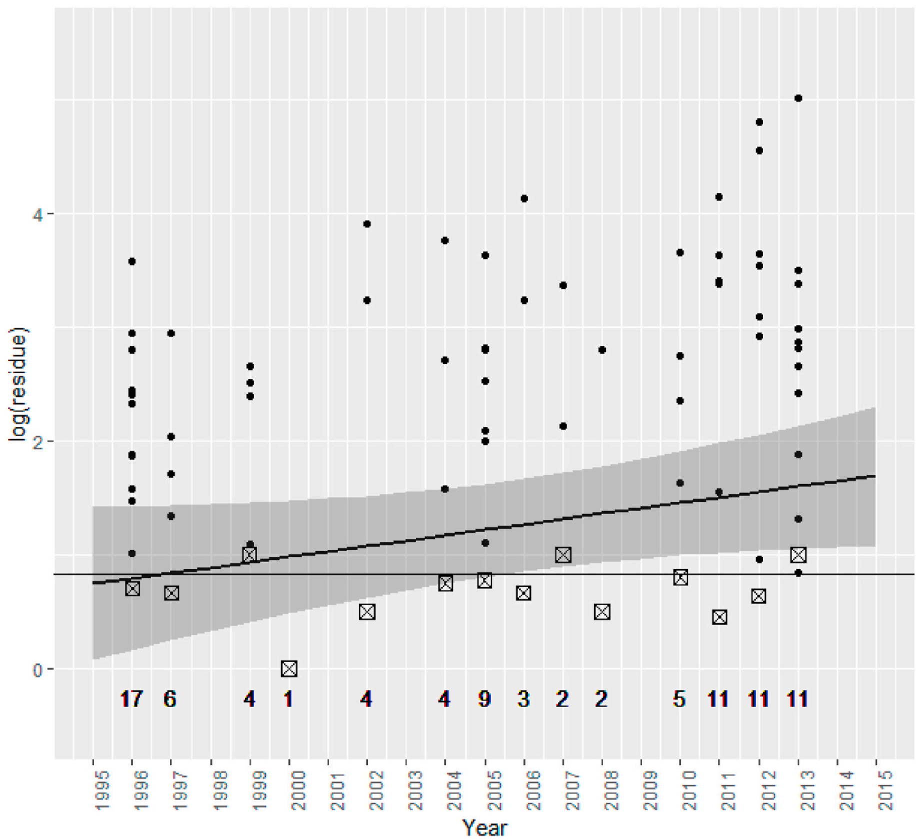

Fig. 3. Observed difenacoum residues in Sparrowhawks in Eastern England (black circles) with estimated regional trend (black line) and associated 95% credible interval. Proportion of observed values (above the limit of detection (LOD)) in each year is shown by open boxes with crosses (proportion shown between 0 and 1). Sample size per year (number of recovered Sparrowhawks) is shown by numbers at the base of the panel. Horizontal line indicates the LOD for the residue compound, on the log scale. Note that no samples at all were available from 2001 due to the cessation of sampling during a foot and mouth livestock disease epidemic in this year.

(*Mustela putorius*) in Britain over a similar time period to our study (1992–2016), but there was no overall trend for Common Kestrels (1997–2012; Roos et al., 2021) or Tawny Owls (*Strix aluco*, 1990–2005; Walker et al., 2008b).

Eastern England, where difenacoum concentrations increased in Sparrowhawks, and where mean summed SGAR concentrations were greatest, is the most urbanised and arable region of Britain. In contrast, difenacoum and mean summed SGAR concentrations were lowest in Scotland, which is the least arable and urbanised region. Similar patterns of lower SGAR exposure in Scotland have also been detected in British Barn Owls (Shore et al., 2015) and Common Kestrels (Roos et al., 2021). These exposure patterns may reflect SGAR usage in relation to land cover, with arable in particular being associated with higher SGAR concentrations in European Polecats and Common Kestrels (Sainsbury et al., 2018; Roos et al., 2021).

Arable and urban environments likely have relatively high deployment of SGARs to control rodents around grain stores, foodstuffs, warehouses, industrial and domestic areas (Roos et al., 2021). Indeed, Hughes et al. (2013) found that 76–86% of Scottish arable farms were using SGARs during 2000–2010, and the proportion of arable land in other regions was at least three times greater than in Scotland (Supplementary Material S1). Assuming that SGAR usage around Scottish arable farms is representative of elsewhere in Britain, this would mean substantially greater SGAR deployment in England and Wales, which could explain the regional exposure patterns in the results.

However, a limitation of our study, and more generally, is the lack of available spatio-temporal information for the use of SGARs by industrial and domestic users that could be used to compare with patterns of exposure in wildlife. It is also unknown exactly where the Sparrowhawks used in this study had originated and accumulated any SGARs prior to death. Some birds may have been migrants or have dispersed between regions within Britain shortly before being recovered, which would undermine any inferences of regional patterns of contamination. However, the large regions of analysis encapsulated the majority of dispersal distances of British Sparrowhawks (Newton, 1986), which should limit spatial mismatch between the exposure and recovery locations. Nevertheless, it is essentially unknown where and when individual birds were exposed to SGARs.

Sparrowhawks probably encounter SGARs by eating passerine birds that have themselves become contaminated by SGARs delivered in bait boxes, which are simply plastic boxes with a tunnel entrance that are used to deliver bait to rodents. Walther et al. (2021) found that typical bait boxes are insecure for non-target wildlife, with SGAR residues found in 28% of songbirds around German farms that used them, as the birds probably entered the boxes to consume bait. However, Dowding et al. (2010) found that 58% of West European Hedgehogs (*Erinaceus europaeus*) in Britain contained SGAR residues, presumably derived from invertebrate prey. This means that songbirds may also consume SGARs by feeding on contaminated invertebrates that have entered bait boxes, or come into contact with rodenticides through their misuse. Indeed, Vyas (2017) found that rodenticide contamination of birds other than raptors was widespread across several regions of the world, resulting from direct consumption of bait or by eating exposed prey. However, Vyas (2017) considered that incidents of SGAR contamination were likely under-recorded, due to lack of awareness or monitoring.

There was strong evidence in our study that adult Sparrowhawks had greater SGAR (difenacoum) concentrations than juveniles, reflecting a greater exposure for older birds, or a greater accumulation of residues with age. Higher concentrations of SGARs in older individuals have been reported for Common Kestrels (Roos et al., 2021), American Mink (*Neovison vison*; Ruiz-Suárez et al., 2016), European Polecats (Sainsbury et al., 2018), but not for Tawny Owls (Walker et al., 2008b). Sparrowhawks are relatively short-lived birds, with a typical lifespan of four years (Robinson, 2005), so significant accumulation of SGAR may be rapid.

Higher SGAR concentrations were also detected in male

Sparrowhawks, which are smaller than females, and tend to favour smaller prey, such as the songbirds that were widely contaminated with SGARs in Germany (Newton, 1986; Walther et al., 2021). However, females could also lose SGARs through transfer to their eggs, as reported or suspected for SGARs and other contaminants in birds (Kubota et al., 2013; Huang et al., 2016). The dynamics of SGAR accumulation and transfer are poorly understood, including how long the compounds are retained in predatory birds and how this may increase the risk of sub-lethal effects in older or smaller individuals. We concur with Rattner and Harvey (2021) that further research on these topics would be valuable.

5. Conclusions

In summary, the results demonstrate extensive exposure of British Sparrowhawks to SGARs, and reveal some variation in spatio-temporal trends over two decades. In line with the hypotheses, SGAR contamination was highest in adult birds and had increased significantly over time, but only in eastern England. As expected, concentrations were lowest in the least urbanised or arable region (Scotland). Contrary to expectations, SGAR concentrations were greater in males than in females, which may reflect a male bias towards preying on potentially contaminated songbirds, or offloading of SGAR residues by females during egg-laying.

The detectable SGARs within most of the Sparrowhawks suggests that the avian prey pathway is widely contaminated in Britain, as potentially in Germany (Walther et al., 2021) and Canada (Thomas et al., 2011). The results support the proposal of Shore et al. (2018) that the avian trophic pathway is another important means of predators ingesting rodenticides worldwide, wherever SGARs are widely used, alongside the well-known contamination pathway via rodents. This growing evidence suggests that the mode and control of rodenticide deployment (including the design of rodent bait-boxes) could be reviewed to reduce the accessibility of poisons to non-target species.

Further work is needed to understand the potential role of SGARs in predator population demographics via lethal or sub-lethal effects, and, ultimately, how SGAR exposure is related to the population declines of predators like Sparrowhawks (Woodward et al., 2020) and Common Kestrels (Roos et al., 2021). Indeed, bird-eating raptors, such as hawks and falcons, are frequently found in habitats around the world where SGAR usage is generally common for rodent control, including in farmland and urban areas (Cramp & Simmons, 1980; Meyer and Kaukeinen, 2015; Boal and Dykstra, 2018; Shore, 2018; McPherson et al., 2021). Our results showing the significance of the avian trophic transfer pathway, in addition to the rodent pathway, therefore indicates that a broad range of predators and their prey species may be at potential risk of SGAR contamination.

Credit author statement

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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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.120269.

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