

Use of sewage treatment works as foraging sites by insectivorous bats

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Abstract

Sewage treatment works (STWs) with percolating filter beds are known to provide profitable foraging areas for insectivorous birds because of their association with high macroinvertebrate densities. Fly larvae developing on filter beds at STWs may similarly provide a valuable resource for foraging bats. Over the last two decades, however, there has been a decline in filter beds towards a system of 'activated sludge'. Insects and bat activity were surveyed at 30 sites in Scotland using these two different types of sewage treatment in order to assess the possible implications of these changes for foraging bats. Bat activity (number of passes) recorded from broad-band bat detectors was quantified at three points within each site. The biomass of aerial insects, sampled over the same period as the detector surveys, was measured using a suction trap. The biomass of insects and activity of *Pipistrellus* spp. were significantly higher at filter beds than at activated sludge sites. In addition, although foraging activity of *Pipistrellus* spp. at filter beds was comparable to that of adjacent 'good' foraging habitat, foraging at activated sludge sites was considerably lower. This study indicates the high potential value of an anthropogenic process to foraging bats, particularly in a landscape where their insect prey has undergone a marked decline, and suggests that the current preference for activated sludge systems is likely to reduce the value of treatment works as foraging sites for bats.

Introduction

Sewage treatment works (STWs) as wildlife habitats

Urbanization by expanding human populations can reduce native biological diversity by reducing the amount and quality of habitat available for wildlife and by the fragmentation of remaining habitats (e.g. Marzluff, Gehlbach & Manuwal, 1998). In some instances, species vulnerable to habitat loss such as bats are able to exploit man-made structures and environments that may provide feeding opportunities and shelter. Some bat species now commonly use buildings as maternity roosts (Kunz & Reynolds, 2003) and exploit foraging opportunities provided by streetlamps that can attract large numbers of insects (Rydell, 1992a).

STWs have long been recognized as potentially valuable foraging areas for birds (e.g. Boyd, 1957; Fuller & Glue, 1980) because of the availability of invertebrate prey. STWs can encompass a diverse range of foraging habitats such as wetland areas and stabilization ponds that can attract and support many wader, waterfowl and passerine species (e.g. Evans & Harris, 1994; Frederick & McGehee, 1994; Gough, Gillings & Vickery, 2003). At sites with percolating filter beds, high densities of macroinvertebrates (e.g. oligochaete worms, crustacea and insects), which develop and/or live on

the filter beds, provide food for many avian species, particularly pipits, wagtails, hirundines and starlings (Fuller & Glue, 1980, 1981; Feare, 1984; Gough *et al.*, 2003). Another group of animals that may benefit from high densities of aerial insects are insectivorous bats, but whether bats use such sites, and how they may be affected by changes in operational practice, is unknown.

Status and conservation of bats in Europe

There is evidence that many bat species in Europe have undergone large population declines during the 20th century (e.g. Stebbings, 1988; Harris *et al.*, 1995). One of the driving causes of these declines is believed to be the loss of roosting and foraging habitat (Stebbing, 1988; Walsh, Harris & Hutson, 1995; Walsh & Harris, 1996a, b). In the UK all species of bats and their roosts are protected under UK [Wildlife and Countryside Act 1981 (as amended)] and international legislation, but foraging sites remain vulnerable to development and changes in land use (Hutson, 1993). A UK-wide bat survey in the 1990s found that habitats favoured by foraging bats were undergoing rapid rates of loss within the UK, and suggested that this may be limiting bats in some areas particularly within arable and pastoral landscapes (Barr *et al.*, 1993; Walsh *et al.*, 1995). Declines in insect abundance over the last 30 years,

associated with the intensification of agriculture, have been linked to declines in farmland bird populations (e.g. Benton *et al.*, 2002) and have been suggested as a contributory factor in the decline of bat populations (Stebbins, 1988; Gerell & Gerell-Lundberg, 1993).

STWs: operational practice

The two main types of secondary sewage treatment are percolating (or biological/trickling) filter beds and activated sludge (Gray, 2005). At filter bed sites, after a screening and sedimentation process, waste water is sprayed over inert material and a microbial biomass, consisting of bacteria, fungi, protozoa and other mesofauna, develops as a film over the surface. This film supports a wide diversity of macroinvertebrates, including dipteran fly larvae that feed upon it (Curds & Hawkes, 1975; Learner & Chawner, 1998; Gray, 2005). In contrast, activated sludge treatment is a process in which a mixture of sewage and bacteria-laden sludge is agitated and aerated, making it inhospitable for most aquatic species (Gray, 2005). Activated sludge is now the dominant system for STWs serving populations of over 50 000, although filter beds are still commonly used for treating sewage from smaller populations (Learner, 2000; Gray, 2005).

The aim of this study was to investigate the use of STWs as foraging sites by bats, and specifically whether differences in their value to foraging bats exist between operational types. The following questions were addressed:

1. How does the abundance of nocturnal aerial insects differ between sewage work types?
2. Do the species of bat, and the levels of bat activity, differ between sewage work types?
3. What level of foraging resources do sewage works provide?
 - i. Do levels of bat activity at a sewage works simply reflect surrounding levels of activity?
 - ii. How does bat activity inside the sewage works compare with activity in habitats considered important for foraging bats?

Materials and methods

Study sites

A total of 30 STWs was surveyed across central and southern Scotland between 11 June and 21 August 2003 (Table 1). Of these, 18 were filter bed and 12 were activated sludge treatment works and were under the operational control of Scottish Water. STW selection was based on the information provided by Scottish Water and such that any bias in size (population served), location (latitude, longitude and altitude) and surrounding habitat towards operational type was minimized (Table 1). The size of the STW ranged from 462 to 42 202 population served, and there was no significant difference between the two types (Mann–Whitney *U*-test $W_{18,12} = 260$, $P = 0.43$).

Table 1 Locations and attributes of sewage treatment work sites visited

Site name	STW type	Population served	Grid reference	Altitude (m)	Date
Alva	AS	4673	NS 874966	10	12/08/03
Armadale	PF	9770	NS 937695	130	21/07/03
Ashgill	AS	1069	NS 789503	100	20/08/03
Avonbridge	PF	689	NS 914728	140	04/08/03
Balfron	PF	1412	NS 548883	50	11/08/03
Bathgate	PF	10 150	NS 961705	120	17/06/03
Bridgend	PF	940	NT 043759	80	14/07/03
Buchlyvie	AS	469	NS 574942	30	31/07/03
Callander	PF	2381	NN 636072	70	08/07/03
Carstairs Junction	PF	2752	NS 962451	190	25/07/03
Coursington	AS	6568	NS 757578	60	21/08/03
Denny	AS	10 677	NS 821829	30	13/08/03
Doune	PF	1235	NN 729008	10	11/06/03
Dunblane	AS	7375	NN 782005	70	12/06/03
Dunnswood	AS	29 510	NS 781772	60	16/07/03
Fallin	PF	2447	NS 836923	10	23/06/03
Fauldhouse	PF	4874	NS 942604	190	30/07/03
Fintry	AS	462	NS 614873	80	09/07/03
Gorebridge	PF	4000	NT 341613	110	15/07/03
Killearn	AS	3200	NS 516845	30	25/06/03
Linlithgow	PF	12 200	NS 986779	30	22/07/03
Maudslie	PF	18 364	NS 786503	40	14/08/03
Peebles	PF	7000	NT 272 398	160	11/07/03
Penicuik	AS	13 500	NT 246609	150	10/07/03
Plains	PF	2376	NS 797664	150	15/08/03
Plean	AS	1518	NS 842871	30	16/06/03
Stirling	AS	42 202	NS 808934	10	01/08/03
Strathblane	PF	2019	NS 547802	40	06/08/03
Westfield	PF	570	NS 939727	110	26/06/03
Winchburgh	PF	2810	NT 092744	80	24/06/03

AS, activated sludge sites; PF, percolating filter bed sites.

Insect sampling

A 9-inch-diameter Johnson–Taylor insect suction trap (Johnson & Taylor, 1955) was used to assess the availability of aerial insects at each STW. The suction trap was positioned in a central location relative to the bat point counts. It was operated at the maximum speed ($850 \text{ m}^3 \text{ h}^{-1}$) from half an hour after dusk for 2 h to cover the same time period as the bat surveys. Insects captured were identified to order or suborder level using Chinery (1993), and stored in 100% ethanol. The number of insects captured during each 2-h session was converted to density per 100 m^3 of air. Once all samples had been collected and identified, the wet weight of insects was measured to the nearest 0.001 g to give biomass per sample.

The diets of the two *Pipistrelle* species that are widespread in the UK, *Pipistrellus pipistrellus* and *Pipistrellus pygmaeus*, consist largely of the dipteran suborder Nematocera (Barlow, 1997). In order to assess long-term changes in Nematocera abundance, a dataset of arthropods captured by a Rothamsted-type 12.2-m-high suction trap (Macaulay,

Tatchell & Taylor, 1988) operating at Stirling University between 1972 and 1998 was examined. A paper describing long-term changes in the abundance of insect orders from this dataset has been published (Benton *et al.*, 2002). Previously unpublished data on Nematocera are presented in the current paper. The trend in Nematocera was identified using a generalized additive model, confidence intervals were generated using bootstrap resamples, and the trend was standardized by scaling it to start at 1.0. See Benton *et al.* (2002) for a full description of the methods and analysis.

Monitoring bat activity

Point counts were used to assess bat activity. At each site 15-min recordings were made at each of three locations within the STW. In addition, 2×15 -min recordings were made along river banks upstream from the sewage outlet, 50 and 75 m outside the STW at 23 sites (15 filter beds, eight activated sludge), as activity of *Pipistrellus* spp. may be reduced along rivers downstream of sewage outlets (Vaughan, Jones & Harris, 1996). At the remaining seven sites this was not possible. The median distance from the centre of each STW to the nearest river was 48.3 m (upper and lower interquartiles: 31.1, 84.3 m). The first point count started 30 min after dusk and the last at 110 min after dusk. Between each 15-min recording, there was a gap of 5 min before the next recording was made. The first point count was randomly allocated to an STW or a riparian location adjacent to the works; once the location of this point had been determined, recordings alternated between STWs and riparian locations. At sites where it was not possible to conduct river point counts, an additional non-recording gap of 15 min was left before the next count. The three locations within each STW were a minimum of 25 m apart and situated around the operational part of the works (i.e. filter beds and/or still-water sedimentation tanks). The bat detector was held at elbow height pointing towards the centre of the works. At river sites, the bat detector was directed towards the river. At the start and end of the recordings, air temperature was measured to the nearest 0.1 °C and wind speed was estimated using the Beaufort scale. The average of these readings was used for analytical purposes. Counts were only conducted in dry weather where the temperature at dusk exceeded 10 °C, and the strength of the wind did not exceed Beaufort 4.

Sound recording and analysis

A frequency division bat detector (Batbox Duet, Stag Electronics, Steyning, UK; frequency response 17–120 kHz) was connected to a MiniDisc (Sony MZ-R909 (Japan); frequency response ± 3 dB 20 Hz–20 kHz) and a continuous recording was made at each point count onto a recordable MiniDisc. Frequency division is a broad-band system that records all frequencies continuously, and is sufficient for distinguishing between the genera *Myotis* and *Pipistrellus*,

and between the *Pipistrellus* species (e.g. Vaughan *et al.*, 1996; see sound analysis). We analysed recordings using BatSound v3.31 (Pettersson Elektronik AB, Uppsala, Sweden), with a sampling frequency of 44.1 kHz with 16 bits per sample, and a 512 pt. FFT with Hanning window. One bat pass was defined as a continuous sequence of at least two echolocation calls from a passing bat (Fenton, 1970; Walsh & Harris, 1996a).

Three genera of bat occur in the area where this study was conducted – *Pipistrellus*, *Myotis* and *Plecotus* (Richardson, 2000) – although *Plecotus* is rarely recorded because of its quiet echolocation calls. Calls of *Myotis* and *Pipistrellus* species can be distinguished by differences in call structure. The calls of the two *Myotis* spp. found in the study area, *Myotis daubentonii* and *Myotis nattereri*, are difficult to distinguish, and no further classification was made for this group. The three *Pipistrellus* species present in the UK can be distinguished on the basis of the peak frequency of their search-phase echolocation calls (FMAXE): bat passes with a mean FMAXE of 40–49 kHz, of greater than 52 kHz and of less than 40 kHz were classified as *P. pipistrellus*, *P. pygmaeus* and *Pipistrellus nathusii*, respectively (Jones & van Parijs, 1993; Vaughan, Jones & Harris, 1997a). Bat passes with an FMAXE between 49 and 52 kHz, or with calls unsuitable for analysis, were classed as unknown *Pipistrellus* sp. or unknown bat. Terminal feeding buzzes emitted when attempting prey capture (Griffin, Webster & Michael, 1960) were also counted, and feeding rate was expressed both as the number of feeding buzzes and as the buzz ratio, the ratio of feeding buzzes to bat passes, which provides a measure of foraging effort per unit of flight activity (Vaughan *et al.*, 1996; Wickramasinghe *et al.*, 2003). Sound analysis was carried out blind to the site being analysed.

Habitat availability

Of the 30 STWs surveyed, the majority (28) were in 1 km squares classed as arable or pastoral land, one as marginal upland and one as urban (Countryside Information System v7.02). An Ordnance Survey Land-Form.Plus multiscale model (DTM) (©Crown Copyright Ordnance Survey. An EDINA Digimap/JISC supplied service) was obtained for the study sites, allowing topographical features such as vegetation type, rivers, buildings, etc., to be generated in a geographic information system (ArcView GIS v3.2, ESRI). For most sites, a scale of 1:2500 was used, but for some STWs near larger conurbations ($n = 7$), the scale was 1:1250. The proportion of different habitats within a 50 m radius of the suction trap position and a 500 m radius from the centre of the STW was calculated. Habitat around the suction trap was categorized as grassland, water (e.g. rivers), concrete (e.g. roads, paving), woodland and filter beds (or open still-water tanks at activated sludge sites). Habitat around the STW was categorized as woodland, agricultural, water and built-up land. Although 50 and 500 m are arbitrary figures, they provide a broad picture of the habitat immediately at, and around, each site enabling any bias in habitat at, and surrounding, the two types of STW to be identified.

Table 2 Classification of bat passes recorded at sewage treatment works

Bat pass classification	Number	% of all bat passes
<i>Pipistrellus</i> spp.	3926	69.6
<i>Myotis</i> spp.	338	6.0
Unknown bat spp.	1380	24.4
<i>Pipistrellus pygmaeus</i>	2609	46.2
<i>Pipistrellus pipistrellus</i>	135	2.4
<i>Pipistrellus nathusii</i>	5	0.1
Unknown <i>Pipistrellus</i> spp.	1177	20.9
Social call	1015	
Feeding buzz	422	
All bat passes	5644	100

Although five passes with an average FMAXE <40 kHz were recorded at three sites, further surveying is required before the presence of *P. nathusii* can be confirmed at these sites.

FMAXE, peak frequency of search-phase echolocation calls.

Data analysis

Because the proportion of *Pipistrellus* spp. passes classified as *P. pipistrellus* was very low (Table 2), we have assumed that the majority of unidentified *Pipistrellus* sp. passes are also *P. pygmaeus*, and for analysis purposes all passes classified as *Pipistrellus* spp. were used. Bat activity was quantified as the total number of *Pipistrellus* spp. and *Myotis* spp. passes at each site or, for comparative analyses with riparian sites outside the STW, the mean number of passes. Although the number of bat passes counted over a specified length of transect or time period does not allow the number of bats using that site to be quantified, it does provide a measure of activity at that site, enabling comparisons between sites (Fenton, 1970).

Data were transformed, where necessary, to achieve normality and homoscedasticity, or non-parametric tests were adopted. The approach used for general linear models (GLMs) was the inclusion of a number of explanatory variables with their interactions (two-way interactions were the maximum used) in a starting model followed by model simplification through stepwise elimination of non-significant explanatory variables. MANOVAs were used to investigate differences in habitat between sewage treatment type. Statistical analyses were carried out using Minitab release 13.1 (Ryan & Joiner, 1994) and Genstat 5 release 4.1 (IACR–Rothamsted) with a significance level of 5%. All statistical tests conducted were two tailed, and errors are expressed as standard errors (SE) of the mean unless otherwise stated.

Results

Insect availability

Almost all the insects captured in the suction trap were in the dipteran suborder Nematocera, with a median percentage of 99.9 and 100 at filter bed and activated sludge sites, respectively. The other two suborders of Diptera (Brachycera and Cyclorrhapha), and seven other orders (Trichop-

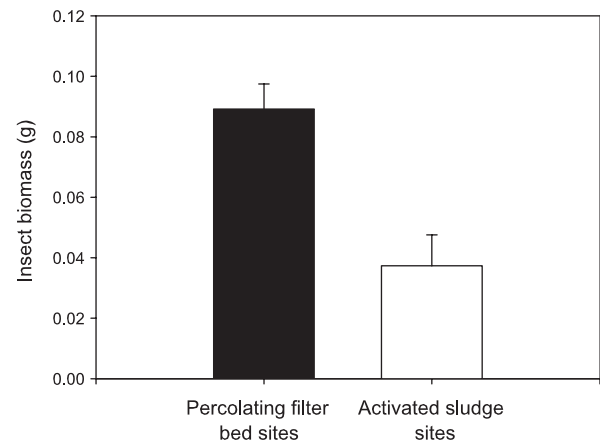


Figure 1 Adjusted mean biomass (g) of insects collected during 2-h suction trap sessions at filter bed sites ($n=18$) and activated sludge sites ($n=12$). Error bars are standard errors of the mean.

tera, Coleoptera, Hemiptera, Thysanoptera, Lepidoptera, Hymenoptera and Psocoptera) were represented by very small numbers (<5 individuals per site at a small number of sites), with the exception of one site where caddis flies (Trichoptera: caddis flies) comprised 16.4% of the total number caught. On average, grass (mostly short mown grass, plus a small proportion of long grass) accounted for the highest proportion of habitat within a 50 m radius of the suction trap at each site. There were no significant differences in the habitat surrounding the suction trap between the two sewage treatment types from either multivariate tests (Wilks $\lambda = 0.731$, $F_{5,24} = 1.764$, $P = 0.16$) or univariate tests of each habitat category.

Biomass and total density of insects were significantly correlated (Pearson correlation coefficient $r_{30} = 0.49$, $P = 0.006$). A GLM was constructed with insect biomass as the dependent variable, and STW type (factor), temperature, size, wind and date (covariates) as explanatory variables. All two-way interactions between explanatory variables were included, excluding those with date. The final model consisted of only STW type and temperature. The biomass of insects at filter bed sites was significantly greater than at activated sludge sites [$F_{1,27} = 14.85$, $P = 0.001$; $\beta = 0.026$, $SE = 0.007$ (filter bed sites); Fig. 1] and was positively correlated with temperature ($F_{1,27} = 4.83$, $P = 0.037$; $\beta = 0.006$, $SE = 0.003$). STW type and temperature explained 32.3% of the variation observed in insect biomass between sites. Using density of insects (ln transformed) as a measure of insect availability gave similar results, with higher numbers of insects at percolating filter beds than activated sludge sites [$F_{1,25} = 9.68$, $P = 0.005$; $\beta = 0.552$, $SE = 0.177$ (filter bed sites)].

Long-term changes in Nematocera abundance

The numbers of Nematocera counted from the Stirling University suction trap have declined over the period

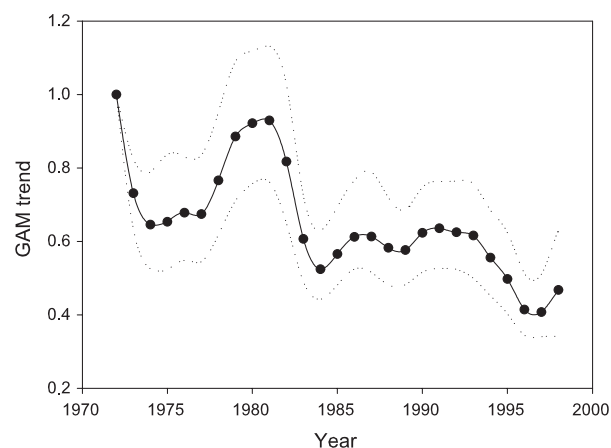


Figure 2 Trend in the number of Nematocera flies caught over 27 years by a suction trap at Stirling University. The trend is the partial fits for a year within a GAM. A 12 d.f. spline was chosen as the best model of the trend. The partial fits are standardized so year 1 = 1. Data supplied by T. G. Benton. See Benton *et al.* (2002) for further details.

1972–1998 (Fig. 2). This decline has not been linear and periods of decline (e.g. mid-1970s, mid-1990s) have been interspersed with periods of high abundance (e.g. early 1980s). The abundance in 1998 (as a fraction of 1972) was 0.47 (using mean counts per year).

Bat activity

Bats were recorded at 27 of 30 STWs surveyed: *P. pygmaeus* at 24 STWs, *P. pipistrellus* at 19 STWs and *Myotis* spp. at 10 STWs. In addition, at three sites, passes with a mean FMAXE of less than 40 kHz was recorded, indicating *P. nathusii*. A total of 5644 bat passes were recorded during 34 h of recordings. Of these, c. 70% were classified as *Pipistrellus* spp., 6% as *Myotis* spp. and 24% as unknown bat passes (Table 2). For sites where the total number of bat passes exceeded 10, there was no significant difference in the proportion of passes classified as unknown between STW type ($F_{1,20} = 0.52$, $P = 0.478$). *Pipistrellus pygmaeus* made up the vast majority of the identified *Pipistrellus* passes: of those passes classified to species, 95% were *P. pygmaeus*.

Habitat availability around sewage works

Within a 500 m radius of each STW, 'agricultural' land including arable, pasture, amenity grass and areas with a mixture of open grassland and low scrub accounted for the greatest proportion of habitat, with built-up land and woodland accounting for the next most common habitats and water (rivers, ponds, etc.) the least. There were no significant differences in the habitat surrounding each site between the two sewage treatment types (Wilks $\lambda = 0.731$, $F_{5,24} = 1.767$, $P = 0.158$), although univariate tests of each habitat category did indicate that there was a significantly higher proportion of built-up land surrounding activated

Table 3 General linear model for the effects of sewage treatment work (STW) type on log-transformed numbers of *Pipistrellus* spp. passes

Source	d.f.	Adjusted		F	P
		mean square	Parameter Coefficient SE		
STW type	1	1.379	-0.3757 0.3618	1.08	0.310
Temperature	1	17.89	0.3739 0.1000	13.99	0.001
Date	1	9.396	-0.0285 0.0105	7.35	0.012
Wind	1	7.431	-0.4171 0.1730	5.81	0.024
% built	1	8.207	0.0607 0.0240	6.42	0.019
STW-type wind	1	25.579	0.7841 0.1753	20.00	0.000
Error	23	1.279			

Temperature, date, wind strength, proportion of built-up land within 500 m of the site (transformed using arcsine square-root), and an interaction term between treatment type and wind strength were included as covariates. For factor 'STW type' the parameter coefficient and associated standard error are for filter bed sites.

sludge sites than filter bed sites ($F_{1,28} = 6.27$, $P = 0.018$; $\beta = -4.526$, $SE = 1.808$).

Comparison between treatment types

A GLM was constructed with total *Pipistrellus* spp. activity (ln transformed) as the dependent variable, STW type as a factor, and temperature, size, wind and date as continuous variables (covariates). All two-way interactions between explanatory variables were included, excluding those with date. As the proportion of 'built-up' land was shown to differ between the two types of STW in the univariate tests of habitat, the variable was transformed using an arcsine square-root and included as a covariate, and in a two-way interaction with STW type.

Pipistrellus spp. activity at filter beds was significantly higher than at activated sludge sites (Table 3, Fig. 3). Temperature and proportion of built-up land correlated positively, and date negatively, with activity, and the final model explained 57.9% of the variation in activity between sites. The parameter estimates and associated significance values for the interaction between wind and type indicated no relationship between *Pipistrellus* spp. activity and wind strength at percolating filter bed sites ($\beta = 0.36$, $P = 0.083$), but a significant negative relationship between *Pipistrellus* spp. activity and wind strength at activated sludge sites ($\beta = -1.201$, $P < 0.001$). There was no significant difference between wind strength at the two STW types ($t_{18,12} = -1.5$, $P = 0.15$).

Myotis spp. were detected at six of 18 percolating filter bed sites and four of 12 activated sludge sites. Because of the large number of sites where no *Myotis* spp. were detected, there were insufficient data to analyse *Myotis* spp. activity in a similar way to *Pipistrellus* spp. activity.

Foraging at STW versus adjacent riparian sites

In order to assess whether bat activity at STW simply reflected activity levels in surrounding riparian areas, a

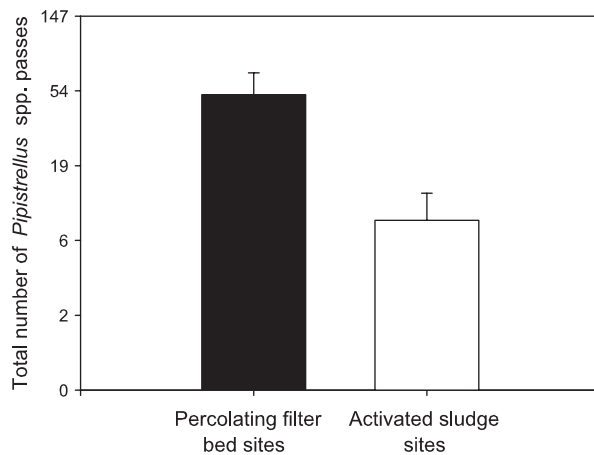


Figure 3 Adjusted total number of *Pipistrellus* spp. passes at filter bed sites ($n=18$) and activated sludge sites ($n=12$). Error bars are standard errors of the mean.

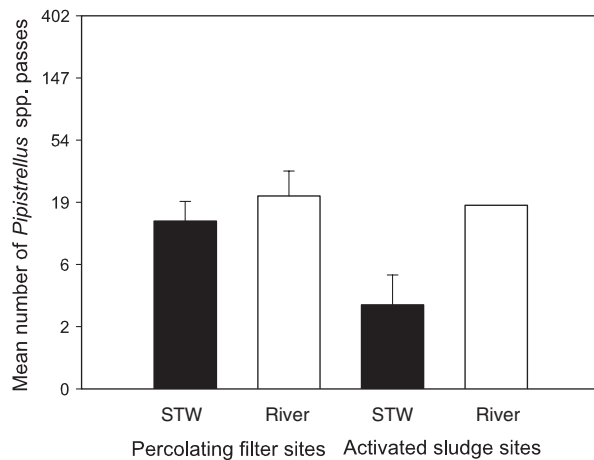


Figure 4 Adjusted mean number of *Pipistrellus* spp. passes at paired sewage treatment work ($n=3$ per site) and adjacent riparian sites ($n=2$ per site). Filter bed sites=13, activated sludge sites=8. Error bars are standard errors of the mean.

GLM was constructed using mean *Pipistrellus* spp. activity (ln transformed) within each STW as the response variable, with mean *Pipistrellus* spp. activity (ln transformed) outside the STW adjacent to a river (covariate), type of STW (factor) and an interaction term as explanatory variables. Mean *Pipistrellus* spp. activity within a STW was positively correlated with *Pipistrellus* spp. activity outside the STW ($F_{1,20} = 6.45$, $P = 0.02$; $\beta = 0.397$, $SE = 0.156$) but STW type remained significant [$F_{1,20} = 6.71$, $P = 0.017$; $\beta = 0.643$, $SE = 0.248$ (filter bed sites)], with more *Pipistrellus* spp. activity at filter bed sites than activated sludge sites. The interaction term was not significant and was removed from the final model, which explained 34.9% of the variation in activity between STW sites. There was no significant difference between the mean number of *Pipistrellus* spp. passes at filter bed sites and paired riparian locations ($t_{15} = -1.13$, $P = 0.28$; Fig. 4).

In contrast, there was a significantly lower number of passes within activated sludge sites in comparison with paired riparian locations ($t_8 = -2.84$, $P = 0.025$; Fig. 4).

There was significantly more *Myotis* spp. activity at riparian locations outside filter bed sites compared with activity within the STW (Wilcoxon matched pair $W_{11} = 65.0$, $P = 0.005$). Once zeros had been excluded, there were insufficient data to test for a difference at activated sludge sites.

Feeding buzzes

On average, 7.5% of passes had feeding buzzes, ranging between 0 and 16.7% per point count, for points with more than 10 passes. There was a significant positive correlation between the number of feeding buzzes and insect biomass at STW (Spearman rank $r_{s,30} = 0.43$, $P = 0.019$). Although there was no significant difference in the number of feeding buzzes between the paired sites for filter bed STWs ($t_{15} = -1.39$, $P = 0.185$), there were significantly fewer feeding buzzes within activated sludge sites than at riparian locations adjacent to them ($t_8 = 2.56$, $P = 0.038$). Similarly, there was no significant difference in the buzz ratios between the paired sites for filter bed STWs (Wilcoxon statistic = 52.0, $P = 1.0$, $n = 15$), but there was a significantly lower buzz ratio at activated sludge sites in comparison with paired riparian sites (Wilcoxon statistic = 21.0, $P = 0.036$, $n = 8$).

Discussion

Results from this study show that bats commonly feed at STWs, but that the type of secondary treatment used at these sites influences the biomass and number of nocturnal aerial insects and consequently the value of the site to foraging bats, in particular *P. pygmaeus*. Levels of activity at filter bed sites were considerably higher than those at activated sludge sites, and whereas activity over filter beds was comparable to nearby riparian sites, activity at activated sludge sites was significantly lower. Three specific questions regarding insect and bat activity at STWs were outlined in the introduction to this study, and these are addressed below.

How does the abundance of nocturnal aerial insects differ between sewage work types?

In this study, the biomass of nocturnal aerial insects sampled by a suction trap at STWs that used activated sludge as a secondary treatment was only 42% of the biomass of insects at percolating filter sites. With the exception of Thysanoptera (Thrips), all the orders representing the suction trap samples have been found in dietary analyses of *Pipistrellus* spp. and *Myotis* spp. (reviewed in Vaughan, 1997), indicating that these samples are a useful measure of the availability of insects to the bats detected at the STW. The majority of insects captured belonged to the dipteran suborder Nematocera, which is the main insect

prey group for both *P. pygmaeus* and *P. pipistrellus* (Barlow, 1997).

Do the species of bat, and the levels of bat activity, differ between sewage work types?

Bats were detected at 90% of STWs visited and feeding buzzes were recorded at 67% of sites where bats were detected, confirming that bats were actively foraging at STWs. A higher number of bat passes were classified as unidentified bat or unidentified *Pipistrellus* spp. than has been documented in similar studies (e.g. Vaughan *et al.*, 1996). Many of these calls were quite faint and the background noise of the STWs sometimes made classification problematic. Nevertheless, the proportions of calls assigned to genera or species were comparable to proportions of population estimates in Scotland (although these population estimates had a low level of confidence attached; Harris *et al.*, 1995), and the dominance of *P. pygmaeus* as the more common *Pipistrellus* species in Scotland has been noted previously (Jones & van Parijs, 1993). The level of activity between the two types of treatment works differed substantially: the total number of *Pipistrellus* spp. passes recorded at activated sludge sites was 57% of those recorded at percolating filter sites. As *P. pygmaeus* use buildings extensively as maternity sites in summer (e.g. Altringham, 2003), it is possible that the positive association between built-up land and number of passes reflects a higher number of roosts within the vicinity of STWs with a larger proportion of built-up land nearby. Wind was negatively correlated with activity at activated sludge sites but had little effect at filter bed sites. As there was no significant difference in the strength of wind recorded at the two treatment types, it is possible that this finding is due to the reduced availability of insects at activated sludge sites given that wind should disperse lower densities of insects more readily than it does high densities.

What level of foraging resources do sewage works provide?

Do levels of *Pipistrellus* spp. activity at sewage works simply reflect surrounding levels of activity?

Overall, there was no significant difference in the habitat surrounding the two types of STW, although the proportion of built-up land was higher around activated sludge sites than filter beds. The inclusion of this variable in the model of *Pipistrellus* spp. activity did not affect the significance of STW type as an explanatory variable for activity. Secondly, although there was a significant positive correlation between *Pipistrellus* spp. activity within and outside the STW, the type of treatment works remained significant. This indicates that the difference in *Pipistrellus* spp. activity found between filter bed and activated sludge sites is not an artefact of differences in surrounding habitat or bat populations, and that higher activity at filter bed sites is due to the presence of the filter beds on which insects develop.

How does bat activity inside sewage works compare with activity in habitats considered important for foraging bats?

In general, freshwater habitats are considered good foraging areas for bats due to high insect densities, and high levels of *Pipistrellus* spp. activity have repeatedly been recorded over rivers, lakes and other riparian habitats (e.g. Swift & Racey, 1983; Racey & Swift, 1985; Walsh & Harris, 1996a; Vaughan, Jones & Harris, 1997b). Of the two commonly recorded species of *Pipistrellus* in the UK, the 55 kHz phonic type (now *P. pygmaeus*) is particularly associated with riparian habitats and this is reflected in their diet (Barlow, 1997; Vaughan *et al.*, 1997b). Data from the present study indicate that while activity within filter bed sites compares favourably with riparian habitat outside the STW (87% of levels at paired riparian sites), activity within activated sludge sites was considerably lower than adjacent riparian sites (46% of levels at paired riparian sites). In addition, both the number of feeding buzzes and the foraging effort per echolocation call (buzz ratio) were significantly higher at riparian locations outside activated sludge sites. In contrast, there was no difference between feeding activity at filter bed sites and adjacent riparian locations. Although analyses of *Myotis* spp. passes were limited, they do indicate a different pattern to *P. pygmaeus*, in that activity levels were significantly lower within filter bed sites than at adjacent riparian sites. Of all the species likely to have been recorded in this study, the association between water and *Myotis daubentonii* is particularly marked as this species feeds largely on insect prey from the water surface or just above it (Jones & Rayner, 1988).

Conclusions

In this study the number of feeding buzzes correlated positively with insect biomass across 30 sites (see also Racey & Swift, 1985). This suggests that areas with high insect densities represent good quality foraging sites. In addition, bats may remain loyal to specific foraging areas (e.g. Brigham & Fenton, 1986; Altringham, 2003). Consequently, changes in foraging habitats that reduce insect densities might be expected to impact negatively on bat populations (Gerell & Gerell-Lundberg, 1993; Vaughan *et al.*, 1996). The identification and maintenance of high-quality foraging sites is therefore important for bat conservation.

Although it remains the most abundant and widespread bat species in the UK, estimates from the Annual Bat Colony Survey in the UK suggest a decline of over 60% between 1978 and 1993 for *Pipistrellus* spp. (Hutson, 1993). As the two phonic types have only recently been separated, it is not possible to assign an estimate of decline to the two species separately. There is also evidence that the abundance of *Pipistrellus* spp. is lower in Scotland as it is nearer the northern edge of its distributional range (Walsh & Harris, 1996b). Because of a restricted annual reproductive rate, bats can be slow to recover from population declines and small population sizes make them particularly susceptible to

further perturbations (Harris *et al.*, 1995; Racey & Entwistle, 2000).

Habitats identified as being the most favourable to bats have suffered large reductions during the past century, in part because of the expansion and intensification of farming (Walsh & Harris, 1996a; Wickramasinghe *et al.*, 2003). In this study we found that the numbers of Nematocera, the main prey group of *P. pygmaeus*, have followed the declines noted for some other arthropod species which appear to be associated with changes in agricultural practices over the last 30 years (Benton *et al.*, 2002). Benton *et al.* (2002) suggest that trends identified from the suction trap at Stirling University are representative of a considerable geographical area. Given that the mean distance of Stirling University to the STWs visited in this study is only 29.4 ± 3.2 km, it is likely that trends observed from changes in Nematocera numbers at this suction trap are reflected over the wider geographical area covered by these sites. In the current study insect biomass and bat activity was only surveyed over a 3-month period (June–August). Studies of adult fly activity at filter bed sites, however, show peak numbers for some species occurring in spring, whereas in other species peak numbers are found during summer or autumn (Learner, 2000). This suggests that filter beds may provide a foraging resource for bats throughout the active season, and possibly even during arousal episodes from hibernation as flies can be captured above filter beds throughout winter, albeit in lower numbers (Learner, 2000). Such benefits, however, appear to differ between bat species presumably because of differences in foraging style and diet. In Scotland, bat diversity is low and this study relates largely to *P. pygmaeus*. In other parts of the UK, where species diversity is greater, patterns of foraging at STWs may differ. Other than species in the *Pipistrellus* genus, other European bat species that feed on large numbers of nematoceran Diptera (but do not forage predominately low over water surfaces) and may therefore forage at STWs include *Rhinolophus hipposideros*, *Myotis brandtii*, *Myotis mystacinus*, *M. nattereri*, *Nyctalus leisleri*, *Nyctalus noctula* (reviewed in Vaughan, 1997), *Eptesicus nilssoni* (Gajdosik & Gaisler, 2004) and *Vespertilio murinus* (Rydell, 1992b).

Some animals are particularly adept at exploiting opportunities created by man-made structures, not intentionally designed for them. For species whose populations are limited by a lack of fundamental resources, such as resting (or roosting/nesting) and foraging sites, such structures can represent good conservation value (e.g. buildings with suitable cavities for the endangered lesser kestrel *Falco naumanni*; Franco, Marques & Sutherland, 2005). This is increasingly being recognized and in some quarters there is encouragement for buildings to incorporate more wildlife-friendly features (e.g. Greater London Authority, 2002). Species able to capitalize on such features, however, remain vulnerable to human whim and technological changes. Many bat species roost in artificial structures, but may be excluded when, for example, mines are sealed to prevent human access or roosts in buildings are evicted because of

human disturbance or persecution (Racey & Entwistle, 2000). Rydell (1992a) suggested that by attracting insects, mercury streetlamps provide local patches of food for some bat species and could be important during periods critical for their survival and reproduction. The increased use of more energy-efficient low-pressure sodium lamps, which do not attract insects, in the 1990s may therefore have reduced the value of street lighting to these bats (Rydell, 1992a; Rydell & Racey, 1995). Results from the current study indicate that other man-made structures or anthropogenic processes such as the treatment of sewage using percolating filter beds can provide a valuable foraging resource for bats because of the emergence of aquatic insects whose larvae develop on the beds. Fuller & Glue (1981) suggested that the development of percolating filter beds had created an entirely new avian niche, with their surface macrofauna providing food for highly characteristic assemblages of birds throughout the year. A comparison between the prevalence of bird species at STWs and in the wider countryside indicated the importance of such sites for particular species including the grey wagtail, starling and house martin, all species on the amber list of the Birds of Conservation Concern in the UK (Gough *et al.*, 2003).

When Fuller & Glue (1980) conducted their survey of STWs, percolating filter beds were the most commonly used method of secondary sewage treatment. In 1972 it was estimated that about 50% of sewage given biological oxidation treatment in England and Wales went through filter bed sites, although many more of the 5000 or so STWs employed filter bed rather than activated sludge technology (Gray, 2004). Since 1970, however, the majority of new domestic and municipal STW plants built have been of the activated sludge type (Gray, 2004). Data on sewage treatment type within the area formerly covered by east and west of Scotland Water (now Scottish Water) indicate that percolating filter beds are now only used as a secondary treatment for c. 9% of the population, but represent 55% of the number of sites (total $n = 213$). Filter beds are still commonly used for treating sewage from smaller populations elsewhere in Europe and are common in other temperate regions (Learner & Chawner, 1998). The reasons for the changes in operating practice were in part due to the smaller area of land required for activated sludge systems and the fly nuisance associated with filter beds (Gray, 2005; N. F. Gray, pers. comm.). The benefits of percolating filter bed systems include lower operational costs and energy requirements, reduced noise, technical skill and maintenance requirements (Learner & Chawner, 1998; Gray, 2005). Percolating filter beds also provide benefits to wildlife by providing a foraging resource, and this study has highlighted their use by insectivorous bats.

Although filter beds cover relatively small areas, they are numerous and distributed widely throughout the countryside (Gray, 2005). Most STWs are situated close to buildings that may act as maternity roosts, particularly for *Pipistrellus* spp., and could represent important local foraging patches for pregnant and lactating females, at a time of year when energetic requirements are especially high. This may be

especially important given that sewage works are generally situated within an agricultural landscape that has seen large declines in insect numbers over the last 30 years. The current preference for activated sludge systems is likely to be detrimental to the value of treatment works as foraging sites for insectivorous animals. It is possible, however, that sympathetic habitat management at these sites may help reduce the negative impact of such conversions. Habitat management recommendations for birds arising from a recent survey of treatment works by the British Trust for Ornithology include the creation and maintenance of woodland and wetland habitats (Gough *et al.*, 2003), and these are also likely to be beneficial to foraging bats.

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