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Concentrations and distribution of ^{210}Pb in bird feathers and its potential for tracing age and flight times

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A B S T R A C T

Bird feathers have been widely used as environmental indicators, providing key information on environmental pollution. However, there is little available information on the adsorption of natural radioactivity in bird feathers and consequently, its impact on the field of movement ecology is not yet known. This study investigates the concentration and distribution of ^{210}Pb in wing- and tail-feathers of different bird species with contrasting migratory strategies, and discusses its potential use as a tracer of age and flight times. Adsorption of ^{210}Pb in bird feathers is directly related to the interaction of feathers with air, therefore it is hypothesised that the presence of this radionuclide is proportional to the length of flight times, and is asymmetrically distributed in flight feathers. Consequently, a significant difference is expected between ^{210}Pb concentrations in feathers of long-distance migrants when compared to sedentary species. For this purpose, a total of 45 samples from eight individuals of three bird species with distinct migratory strategies were analysed: a highly aerial and long-distance migratory species (Common swift *Apus apus*), and two largely sedentary species widely distributed across Europe (Great tit *Parus major* and Tawny owl *Strix aluco*). Novel findings show that the content of ^{210}Pb in bird feathers of adult migratory birds is much higher than in sedentary birds or juvenile individuals, demonstrating this naturally occurring radionuclide can provide information about the contact time between feathers and air. Additionally, ^{210}Pb adsorption was not evenly distributed in bird feathers. The findings provide a new method to trace age and flight time of birds using ^{210}Pb in feathers, complementing conventional techniques in bird migration studies.

1. Introduction

Birds play an important role as environmental indicators. Given their sensitivity to habitat change, and the fact that many bird species are conspicuous organisms (i.e., readily recorded or noticed), relatively easy to identify, and their general biology and ecology is well understood, they have been widely used to characterise changes in the quality of the environment (Becker, 2003; Venier and Pearce, 2004; Gregory et al., 2005; Pereira and Cooper, 2006). The most well-known example is the use of birds as indicators of environmental pollution, such as biomagnification of persistent organic pollutants or heavy metals (Sagerup et al., 2009; Goutte et al., 2014; Sebastiano et al., 2014), or the adsorption of artificial radioactive contamination (e.g., Chernobyl accident in 1986; Møller et al., 2007, 2013; Mousseau and Møller, 2013).

Several bird-based investigations on environmental quality have derived from the analysis of bird feathers. Advantages of using feathers in chemical analysis include ease of collection (Becker, 2003), they are directly influenced by the presence of chemical substances in the atmosphere (Rutkowska et al., 2018), and their moulting patterns are often well known (e.g., Jenni and Winkler, 2020). However, research on the adsorption of naturally occurring radioactivity in bird feathers is very scarce, and has so far focused exclusively on seabirds. Only two

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studies, performed on the same set of samples, suggest a direct adsorption of the radionuclides present in the atmosphere by feathers (Skwarzec and Fabisiak, 2007; Boryło et al., 2010). Skwarzec and Fabisiak (2007) estimated that 63% of the ^{210}Po found in bird feathers of ten seabirds species examined from the Polish Baltic Sea was probably adsorbed from air. A similar proportion was estimated by Boryło et al. (2010) for uranium. Additionally, all available studies on this topic concur that seabird feathers tend to accumulate the highest concentrations of polonium (Skwarzec and Fabisiak, 2007; Hansen et al., 2020) and uranium (Boryło et al., 2010), as compared to other organs and tissues. Moreover, studies that determine the concentration of ^{210}Po (Skwarzec and Fabisiak, 2007), and artificial radionuclides such as plutonium isotopes (Strumińska-Parulska et al., 2011), agree that wintering and migratory birds show a higher concentration of these radionuclides in their body as compared to sedentary birds. Nevertheless, the concentration and distribution of naturally occurring ^{210}Pb in bird feathers has not yet been described.

Pb-210 is a naturally occurring radionuclide that is continuously produced in the atmosphere by the decay of gaseous ^{222}Rn (Garcia-Orellana et al., 2006; Baskaran, 2011), which mainly originates in the lithosphere. Pb-210 has a widespread distribution throughout the atmosphere, and its activity is governed only by production rates, decay rates, and removal through scavenging by atmospheric particles. For these reasons, ^{210}Pb is considered an accurate tracer of atmospheric processes (Baskaran, 2011). Lead is a particle-reactive element that is scavenged by aerosols (e.g., fine dust) in the atmosphere, and is therefore carried primarily by advective transport of air masses. In comparison to surface soils, atmospheric aerosols typically present high ^{210}Pb concentrations due to atmospheric adsorption. Pb-210 concentrations are usually proportional to the specific surface area of the particles and their residence time in the atmosphere (Preiss et al., 1996; Garcia-Orellana et al., 2006). Analogously to the adsorption of ^{210}Pb in dust aerosols, ^{210}Pb present in the atmosphere could be directly adsorbed by feathers and accumulated throughout bird migratory routes. Thus, the concentration of ^{210}Pb in bird feathers may provide information on bird ecology, including bird flight times.

Metals, including ^{210}Pb, may collect in feathers through endogenous accumulation, i.e., metals supplied in food that is incorporated in feather structures; and exogenous contamination, i.e., adsorption of metals on the feather surface (Markowski et al., 2013). Considering the properties of ^{210}Pb (production from ^{222}Rn in the atmosphere, particle-reactive), adsorption on the feather surface from the atmosphere is considered to be the main mechanism of ^{210}Pb accumulation in feathers (Skwarzec and Fabisiak, 2007). Feathers grown at different times or locations may present contrasting ^{210}Pb concentrations, reflecting exposure to varying environmental conditions from the previous moult (Dauwe et al., 2003; Jaspers et al., 2004, 2009). For this reason, chick feathers are more likely to better reflect local conditions than adult bird feathers, which may be influenced by atmospheric signals from external areas (Franson and Pain, 2011; Michielsen et al., 2018). Similarly to other particle-reactive chemical compounds present in the atmosphere, such as heavy metals (Jaspers et al., 2008; Malik and Zeb, 2009; Abdullah et al., 2015) or other natural radionuclides (^{210}Po; Skwarzec and Fabisiak, 2007), the degree of interaction between feathers and ^{210}Pb during a bird's flight may also affect the adsorption of ^{210}Pb on feathers. Consequently, migratory birds are expected to show higher activity concentrations than sedentary birds. Knowledge on moulting and migration patterns, as well as the age of the bird, are essential to understand ^{210}Pb concentrations in relation to feather exposure.

This article describes the concentration and distribution of ^{210}Pb in wing and tail feathers for the first time, and discusses the potential use of ^{210}Pb as a tracer of bird age and flight times. For this purpose, feather samples were analysed from juvenile and adult individuals of a highly aerial and long-distance migratory species (Common swift *Apus apus*; hereafter common swift) and contrasted to adult specimens of two largely sedentary species of wide distribution in Europe (Great tit *Parus major*; hereafter great tit and Tawny owl *Strix aluco*; hereafter tawny owl). It is hypothesised that bird feathers which have a higher degree of interaction with air will show the highest concentrations of ^{210}Pb.

2. Material and methods

2.1. Description of the study species

The common swift is a long-distance migratory bird with a large distribution range: it breeds in Europe and Asia and winters in Africa south of the Sahara (Ahmed and Adriaens, 2010; Åkesson et al., 2012). The common swift has been globally classified as of Least Concern (BirdLife International, 2023). This insectivorous species is adapted to life in the air, spending almost the entire part of its life aloft (Bäckman and Alerstam, 2001; Liechti et al., 2013). It is renowned for its superb flying ability, giving both its morphological and physiological adaptations, developed for efficient flight (Henningsson et al., 2008). It is estimated that the common swift spends on average 10 months of the year flying (Hedenström et al., 2016). Therefore, the species should be constantly exposed to air (Åkesson et al., 2012) and its feathers expected to highly represent ^{210}Pb adsorption.

Common swifts have 10 full-length primaries (hereafter P) and 8–11 significantly shorter secondaries (hereafter S) in each wing, and 10 tail feathers or rectrices (hereafter R) (Ginn and Melville, 1983; Chantler and Driessens, 2000; see Fig. 1). Birds moult after the post-breeding migration to their African wintering grounds (Newton, 2009). Although some specimens retain the outermost primary (P10) until the second post-breeding moult, the moulting process is usually complete by the second winter, including all primaries and secondaries (Jukema et al., 2015). The juvenile plumage is partially replaced during their first year of life and their first period in Africa, where swifts moult only their body feathers, smaller wing-coverts, and (in most cases) their tail feathers and secondaries (Chantler and Driessens, 2000; Ahmed and Adriaens, 2010). Juvenile individuals as opposed to adults can readily be recognised by their blunt wings and fine whitish edgings on the body, wings, and tail feathers. Adult individuals have no edges on the body, and wing feathers are notably broader and more rounded than in juvenile individuals (Hume et al., 2016; Jukema et al., 2015).

The great tit is a common bird that occupies a diversity of habitats (Kvist et al., 2003). This passerine is widely distributed throughout Europe, the Middle East, Central and Northern Asia, and parts of North Africa (Perfito et al., 2012; BirdLife International, 2023), and has also been globally classified as of Least Concern (BirdLife International, 2023). The species is defined as largely sedentary, only migrating in exceptional circumstances such as severe winters (Nowakowski and Vähätalo, 2003; Perfito et al., 2012). Therefore, the feathers from this species should have less interaction with air relative to the common swift (for instance, foraging rate of great tits is shown to be reduced with decreasing temperatures; Pakanen et al., 2018), and its feathers expected to have lower concentrations of ^{210}Pb.

Great tit individuals have 10 primaries and 6 shorter secondaries on each wing, and the tail is composed of 12 rectrices (Dhondt, 1973; Pap et al., 2007). Primaries, secondaries, and rectrices are numbered the same way as for the common swift (see Fig. 1). Great tits perform a partial post-juvenile moult after fledging (between late summer and early autumn), in which only part of the body and flight feathers are replaced (Pap et al., 2007; Jenni and Winkler, 2020). Adults undergo a complete moult after breeding (post-nuptial moult) that takes approximately three months (Gosler, 1994). This moult typically starts with the loss of the innermost primary feather (P1), and by the time P3 to P5 have moulted, secondaries, tertials, and tail feathers start dropping simultaneously (Gosler, 1994). The moulting patterns of primary, secondary, and tail feathers are the same as for the common swift and many other passerine species (Newton, 2009; see Fig. 1).

The tawny owl is the most abundant nocturnal raptor in Europe, and it is commonly found in woodlands and urban environments

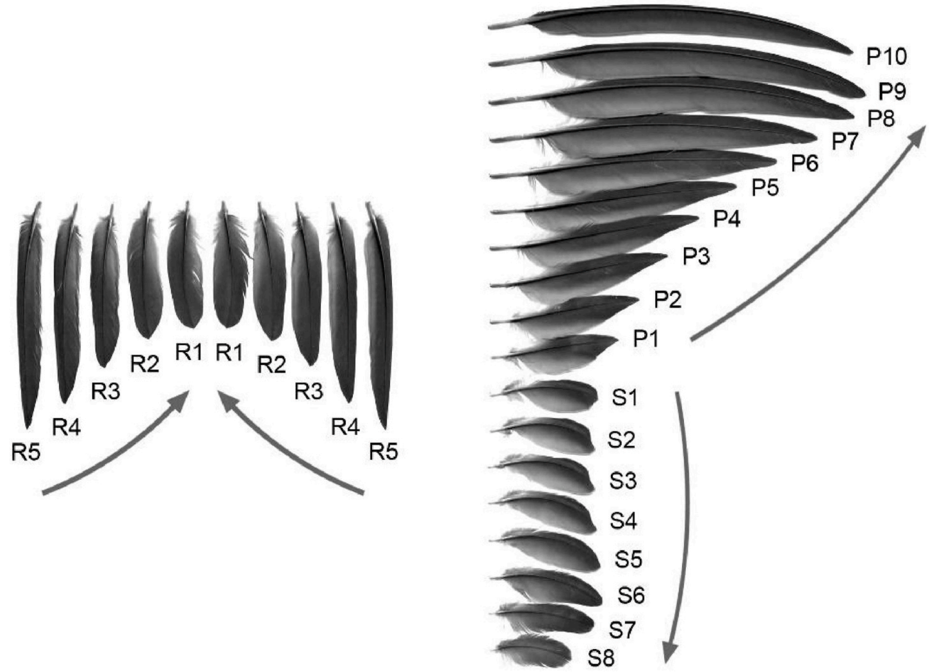

Fig. 1. Wing and tail feathers of an adult common swift individual. Primaries (P), secondaries (S), and tail feathers (rectrices; R) are shown. Primary feathers are numbered from P1, the innermost primary, to P10, the outermost primary. Secondary feathers are numbered from S1, the outermost secondary, to S8-11, the innermost secondaries. Rectrices are numbered from R1, the innermost rectrix, to R5, the outermost rectrix. Primary feathers are renewed from the innermost outwards, in descending order (Chantler and Driessens, 2000). Secondary feathers moult from the outermost (S1) inwards (S8-11), as is the case of most passerine species (Chantler and Driessens, 2000; Newton, 2009). Tail feathers moult centripetally, starting with the outer pair and working inwards (Chantler and Driessens, 2000).
Original source: http://www.michelklemann.nl/verensite/start/index.html.

(López-Peinado et al., 2020; Keller et al., 2020). It is largely distributed across much of Eurasia and North Africa and as the two previous species, it has also been globally classified as of Least Concern (BirdLife International, 2023; Keller et al., 2020). The species is sedentary and highly territorial (Hagemeijer and Blair 1997), as such their feathers are expected to have lower concentrations of ^{210}Pb as compared to common swifts.

Tawny owls have ten primaries, thirteen secondaries and twelve rectrices (Karrel et al., 2013). According to the observed moulting pattern in tawny owls inhabiting northern Europe, breeding individuals typically initiate the moulting process of their remiges and rectrices only after their chicks have successfully fledged. Adult owls begin this process in June, and the duration of the moult spans 77 days (Hirons et al., 2009). In contrast, non-breeding individuals commence moulting earlier in the seasonal cycle (Petty, 1992). First-year birds undergo moulting of body feathers exclusively between September and November (Hirons et al., 2009). Tawny owls are attack predators that typically hunt from perches, prioritizing manoeuvrability and primary propulsion during take-off for effective foraging. Primary feathers are crucial for propulsion, while secondaries are crucial for gliding (Sunde et al., 2003; Hickman et al., 2008). Notably, during periods of food scarcity, tawny owls experience a more pronounced shedding of both primary and secondary feathers. Conversely, in years of abundant prey availability, the focus shifts toward reproductive investment, resulting in a reduced intensity of feather shedding (Petty, 1994).

2.2. Sampling

Bird feathers (hereafter samples) from common swifts were obtained from two different sources and periods: 1) the Torreferrussa Wildlife Rehabilitation Centre in March 2012; and 2) the Barcelona Natural Science Museum in December 2022 (see Table 1). Birds that had been dead for at least two years after their arrival at the respective centres have been selected to allow for ^{210}Pb analysis via ^{210}Po (see below).

Table 1
Summary of sample extraction for each of the study species.

Species	Source	Date of collection	Sample	Date of death
Common swift	Torreferrussa Wildlife Rehabilitation Centre	March 2012	2 adults, 1 juvenile	May 2010 and July 2010, respectively
	Barcelona Natural Science Museum	December 2022	1 adult, 1 juvenile	June 2011
Great tit	Collserola Natural Park	December 2020	1 adult	February 2014
	Barcelona Natural Science Museum	December 2022	1 adult	May 2016
Tawny owl	Torreferrussa Wildlife Rehabilitation Centre	November 2022	1 adult	February 2020

The Torreferrussa Wildlife Rehabilitation Centre provided two adult common swift individuals (both females) which died in May 2010, and a juvenile individual which died in July 2010 (Table 1). The age of the specimens was estimated based on their plumage, and date of death. Thus, the adult individuals were at least 10 months old, whereas the juvenile individual was about one month old. These specimens died soon after they were brought to the centre, and they were kept in one of the freezers at the centre, where samples were collected. The two specimens collected from the Barcelona Natural Science Museum (one adult and one juvenile bird) were aged based on their plumage and date of death. Both were collected in June 2011, and had therefore been deceased for more than 10 years by the date of analysis (Table 1). The specimens had been preserved in a freezer from date of death to sample extraction.

To test the hypothesis of lower concentrations of ^{210}Pb in feathers belonging to the sedentary species as compared to the migratory species, samples from two adult great tit specimens and one specimen of tawny owl were also collected.

Great tit samples were collected from two distinct sources and periods: 1) in December 2020 from a ringer working at the Collserola Natural Park; and 2) in December 2022 from the Barcelona Natural Science Museum. The first specimen was born in April 2011 and was almost three years old when it died in February 2014 (ring code: 3N57538). The second specimen was aged as an adult based on their plumage and date of death, it was collected in May 2016. Both specimens were preserved in a freezer before the sample extraction for analysis, and over 6 years have passed between the estimated date of death and extraction (see Table 1).

Tawny owl samples were collected from the Torreferrussa Wildlife Rehabilitation Centre in November 2022. The specimen was aged as an adult (female) based on their plumage and date of death. The individual was already dead upon arrival at the centre in February 2020, and it had been dead for over two years before sample extraction (see Table 1).

For common swifts, primary (adult 1: P10, P9 and P8; adult 2: P10, P9 and P8; adult 3: P10, P9, P8, P7, P6, P5, P4, P3, P2 and P1; juvenile 1: P10; juvenile 2: P10, P9 and P8), secondary (adult 3: S1, S2, S3 and S4; juvenile 2: S1 and S2) and tail feathers (adult 3: R5, R4, R3, R2 and R1; juvenile 2: R5, R4, R3, R2 and R1) were extracted. For adult 1, distinctions are made between the anterior vane, the posterior vane, and the rachis of P9 and P8 (see Table 2). This was done to discard other potential sources of contamination. For instance, if ^{210}Pb adsorption were via ingestion, a homogenous distribution of this radionuclide in all parts of the feather would be expected (Jaspers et al., 2004). For sedentary species (great tit and tawny owl), only primary feathers were extracted for comparison to those of common swifts. For great tits, only P9, P8, and P7 for both adult specimens were extracted (see Table 2). The outermost primary (P10) was not considered due to its size differential, P10 is less than 10% the size of the next proximal primary. Therefore, ^{210}Pb activity has only been determined from P9, the first fully grown primary after P10 (Pap et al., 2007). For the tawny owl, the first three primaries (P10, P9 and P8) were extracted as done for the common swift individuals. For P9, distinctions are made between the anterior vane, the posterior vane, and the rachis (see Table 2).

All samples (45 in total) were separated in plastic bags (one for each feather) and stored in the freezer of the Environmental Radioactivity Research Laboratory (GRAB) at the Autonomous University of Barcelona (UAB) until analysis.

2.3. Pb-210 determination

Feathers used to determine ^{210}Pb activity were sampled from specimens which had been dead for at least two years, and were frozen until analysis. After two years, activities of ^{210}Pb are in radioactive equilibrium with its decay product nuclide ^{210}Po, and thus ^{210}Pb activities can be determined directly by measuring ^{210}Po activities. Po-210 was quantified at GRAB (UAB) in July 2012 and October 2023 for common swifts, in December 2020 and October 2023 for great tits, and in October 2023 for tawny owl (Sanchez-Cabeza et al., 1998). Samples were weighed and sectioned into smaller fragments, concentrated nitric acid (HNO_3) and hydrochloric acid (HCl) was added to each sample until digested. Po-209 was added ($T_{1/2} = 125$ years) as an internal tracer to control the chemical yield. After digestion, samples were filtered and evaporated on a hotplate. A reagent blank was prepared to determine possible radioactive impurities during the radiochemical procedure. Both ^{209}Po and ^{210}Po were deposited on silver discs and were measured by alpha spectrometry using an Ortec α-spectrometry system. Polonium isotopes were counted for a minimum of 4×10^5 s to minimize counting uncertainty. Recovery of ^{209}Po ranged from 24% to 92%. Relative uncertainties of the reported activities range from 7% to 30% (depending on sample activity) and are mainly derived from alpha counting uncertainties, also consider the uncertainty of ^{209}Po addition (pipetting error and the uncertainty of the solution activity). The Minimum Detectable Activity (MDA) was determined from the background of every detector and considers the counting time and analysed mass for every sample. The results were corrected for decay to the date of death of the birds.

Table 2
Distribution of ^{210}Pb in primaries (P), secondaries (S), and rectrices (R; tail feathers) of adult and juvenile common swift individuals, primary feathers in adult great tit individuals, and primary feathers in an adult tawny owl individual. Note that for the adult common swift individual and the adult tawny owl individual, the anterior vane, the posterior vane, and the rachis (P9 and P8 for the common swift, P9 for the tawny owl) are separated. Pb-210 concentrations (normalized by weight) are shown along with uncertainties. Feathers are ordered according to Fig. 1. Negative values are below MDA.

Species	Individual	Feather type and wing side	^{210}Pb (Bq · kg^{-1})
Common swift	Adult 1	P10, right wing	849 ± 54
		P9, right wing	1065 ± 71
		P8, right wing	1064 ± 73
		P9, left wing, anterior vane	935 ± 70
		P9, left wing, posterior vane	684 ± 50
		P9, left wing, rachis	98 ± 9
		P8, left wing, anterior vane	563 ± 55
		P8, left wing, posterior vane	368 ± 36
		P8, left wing, rachis	93 ± 8
	Adult 2	P10, right wing	823 ± 52
		P9, right wing	486 ± 32
		P8, right wing	736 ± 52
	Adult 3	P10, right wing	1685 ± 80
		P9, right wing	331 ± 15
		P8, right wing	321 ± 14
		P7, right wing	275 ± 15
		P6, right wing	338 ± 18
		P5, right wing	447 ± 18
		P4, right wing	978 ± 39
		P3, right wing	594 ± 33
		P2, right wing	538 ± 32
		P1, right wing	623 ± 42
		S1, right wing	526 ± 39
		S2, right wing	324 ± 38
		S3, right wing	142 ± 27
		S4, right wing	60 ± 19
		R5, right side tail	90 ± 9
		R4, right side tail	97 ± 10
		R3, right side tail	78 ± 14
		R2, right side tail	45 ± 16
		R1, right side tail	50 ± 13
	Juvenile 1	P10, right wing	1 ± 4
	Juvenile 2	P10, right wing	3 ± 1
		P9, right wing	1 ± 1
		P8, right wing	−3 ± 1
		S1, right wing	22 ± 7
		S2, right wing	84 ± 6
		R5, right side tail	16 ± 4
		R4, right side tail	3 ± 7
		R3, right side tail	15 ± 4
		R2, right side tail	−7 ± 11
		R1, right side tail	17 ± 4
Great tit	Adult 1	P9, right wing	−17 ± 14
		P8, right wing	64 ± 10
		P7, right wing	47 ± 10
	Adult 2	P9, left wing	29 ± 4
		P8, left wing	14 ± 4
		P7, left wing	32 ± 5
Tawny owl	Adult 1	P10, right wing	48 ± 3
		P9, right wing, anterior vane	64 ± 3
		P9, right wing, posterior vane	46 ± 2
		P9, right wing, rachis	2 ± 0
		P8, right wing	40 ± 2

2.4. Statistical tests

Normality of ^{210}Po distribution was checked for every subgroup of birds (adult common swift, juvenile common swift, adult great tit, and adult tawny owl). For both common swift groups, distributions were not normal, so a Kruskal-Wallis rank sum test was applied to determine if subgroups were significantly different. A Dunn test with Bonferroni correction was conducted to determine which subgroups presented significant differences when compared to one another. Analyses were carried out using basic R software version 4.1.2 (R Core Team 2021) and R package FSA (Ogle et al., 2023). Significantly, 3 out of the 45 samples were not considered in this analysis because of very low and anomalous activities (see Table 2). In addition, due to the distinction between the anterior vane, the posterior vane, and the rachis for P9 in tawny owls, the posterior vane is considered representative for the whole feather.

3. Results

3.1. Activity concentrations and distribution of ^{210}Pb in flight feathers

The highest ^{210}Pb activity concentrations (i.e., normalized by weight) were observed in primary feathers (P) of the adult common swift individual as compared to the secondary (S) and tail feathers or rectrices (R). In analysed secondary feathers, ^{210}Pb activities were below MDA. ^{210}Pb adsorption was also present in the rectrices, albeit to a lesser extent than in primary feathers (adult 3 in Table 2; Fig. 2a).

Activity concentrations and distribution of ^{210}Pb in flight feathers show evidence of a relation to wing exposition to flight friction. The outermost primary feathers of common swifts analysed (P10) had higher activity concentrations than central primaries (P9–P5) on average, though activity concentration increased substantially in inner feathers (P4–P1; Table 2). Specifically, P10 had higher concentrations than P9 and P8 in two of the three analysed specimens (adult 2 and adult 3 in Table 2), and P9 and P8 had almost identical concentrations in two of the three specimens analysed (adult 1 and adult 3 in Table 2). While ^{210}Pb concentrations in adult 3 were evenly distributed between P9 to P5, P4 showed two to three times higher concentrations than P9 to P5. The distribution of ^{210}Pb was largely stable (although higher than P9 to P5) among P3 and P1 (adult 3 in Table 2).

Regarding the activity concentration in different parts of the primary flight feather, for both P9 and P8 (adult 1), the anterior vane adsorbed more ^{210}Pb as compared to the posterior vane, and the lowest activity concentrations were found in the rachis (Table 2; Fig. 3). It was not possible to determine with certainty the adsorption pattern of ^{210}Pb in the primary feathers of the adult common swift individual. Nevertheless, the adsorption patterns of the adult common swift secondary and rectrix feathers, unlike primary feathers, were clearly determined. Similar to primaries, higher ^{210}Pb concentrations we detected in outermost feathers (S1 and S2, and R5 and R4, respectively; see Fig. 1 and adult 3 in Table 2) and lower concentrations in innermost feathers (S3 and S4, and R2 and R1, respectively; see Fig. 1 and adult 3 in Table 2).

Analysis of juvenile common swift individuals' samples showed very low values of ^{210}Pb concentration in primary feathers (juvenile 1 and 2 in Table 2). Interestingly, analysed secondary feathers (S1 and S2) had higher concentrations as compared to primary feathers in one of the juvenile individuals (juvenile 2 in Table 2). Rectrices of the same individual showed lower activities than secondary feathers, with ^{210}Pb concentrations distributed equivalently between them, with the exception of lower activities detected in R4 and especially R2 (juvenile 2 in

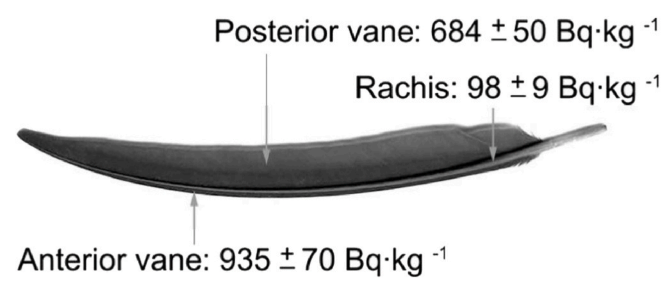

Fig. 3. Distribution of ^{210}Pb concentrations in different parts of a feather. Pb-210 concentrations were divided between anterior vane, posterior vane, and rachis in two primary feathers (P9 and P8) for one of the common swift adult individuals analysed. The figure shows the values for P9 (see adult 1 in Table 2).

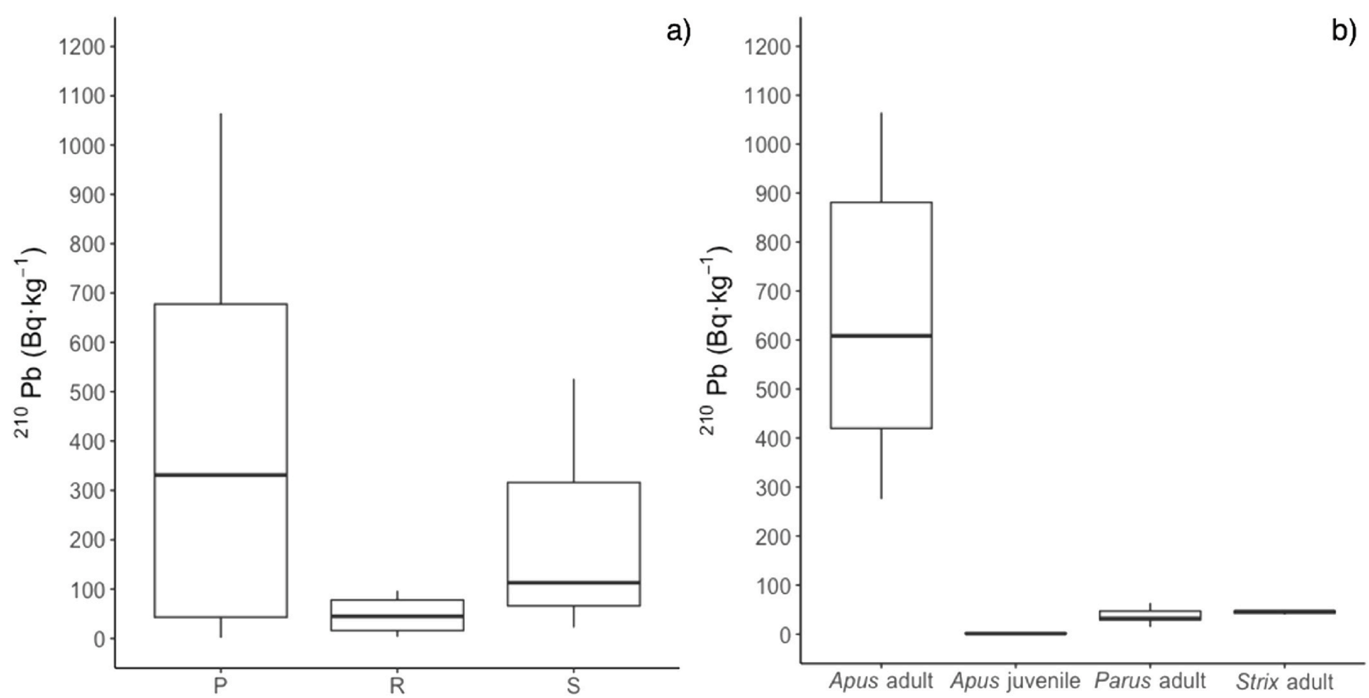

Fig. 2. Pb-210 concentrations in analysed bird specimens. (a) Concentrations of a single adult common swift individual (adult 3 in Table 2) are shown for primary (P), secondary (S), and rectrix (R) feathers, respectively. (b) Differences in concentrations by age (adult vs juvenile common swift; *Apus* adult vs *Apus* juvenile) and migratory strategy (migratory common swift vs sedentary great tit and tawny owl; *Parus* adult and *Strix* adult) are shown for primary (P) feathers only. Note that the ^{210}Pb concentration of the juvenile common swift, i.e., *Apus* juvenile in (b) is below MDA.

Table 2).

Regarding the non-migratory species, analysed primary feathers from the adult great tit individuals (P9, P8 and P7) were found to have similar ^{210}Pb concentrations in both specimens, although activity could not be determined for P9 in one of the two individuals (<MDA; Table 2). Analysed primary feathers for the tawny owl individual also showed an even distribution of ^{210}Pb concentration. Similar to the common swift, the anterior vane was the part of the feather (in this case P9) that adsorbed more ^{210}Pb as compared to the posterior vane, whereas the lowest activity concentrations were found in the rachis (Table 2).

3.2. Activity concentration of ^{210}Pb among age classes and species

When comparing groups, the results from the Kruskal-Wallis and Dunn tests revealed that there were significant differences (p-value <0.05) between the ^{210}Pb concentrations of adult and juvenile common swifts (adjusted p-value <0.001; Fig. 2b). There were also significant differences between adult common swifts and adult great tits (adjusted p-value $= 0.02$; Fig. 2b). However, the concentrations of adult common swifts were not significantly different from those of the tawny owl (adjusted p-value $= 0.22$; Fig. 2b).

4. Discussion

Primary feathers of the common swift adult individual (adult 3 in Table 2) had higher concentrations of ^{210}Pb than secondary and tail feathers. The three primary feathers analysed for the three specimens (P10 to P8) are in the outermost part of the wing. These feathers are those most exposed to air and, therefore, to ^{210}Pb present in the atmosphere (Dauwe et al., 2003; Jaspers et al., 2004). The anterior vane showed higher ^{210}Pb activities, followed by the posterior vane and the rachis. This can be explained by the fact that the anterior vane is narrower than the posterior vane, and is also most exposed to air, with greater ^{210}Pb adsorption potential. The distribution of ^{210}Pb in feathers (i.e., higher concentrations in the most air exposed areas) confirms that this radionuclide is mainly accumulated through adsorption from the atmosphere, not through ingestion as occurs with stable isotopes. Results from previous investigations also support this conclusion (Skwarzec and Fabisiak, 2007). Regarding secondary feathers, it can be concluded that the low ^{210}Pb concentration as compared to primaries is related to lesser exposure to air, as they are located in the innermost section of the wing. Finally, the concentration of ^{210}Pb found in rectrices, although lower than for secondary feathers, was also significant. Importantly, for adult common swifts, it was possible to distinguish a pattern of ^{210}Pb absorption among the first three primary feathers, the first four secondary feathers, and the five rectrices which matches the expected degree of feather exposure to air. In the case of the juvenile common swift individual, the low concentrations of ^{210}Pb, especially in the primary feathers analysed, are indicative of low exposure to air, which is explained by the fact that juvenile birds have only recently learned to fly (Wright et al., 2006). On the contrary, adult individuals of the same species adsorbed much higher ^{210}Pb concentrations due to longer flight times (including migration to their wintering grounds in Africa; Ahmed and Adriaens, 2010; Åkesson et al., 2012), and are therefore more exposed to ^{210}Pb present in the atmosphere.

Results from the great tit and tawny owl adult individuals showed much lower concentrations of ^{210}Pb in primary feathers as compared to adult common swifts. This is consistent with the different migratory strategies of these three species: Whilst the common swift is considered as a high aerial and long-distance migratory species (Åkesson et al., 2012; Liechti et al., 2013), the great tit and the tawny owl are mainly classified as a sedentary species and short-distance flyers. Sedentary species are expected to adsorb less ^{210}Pb in their feathers, especially those whose feeding ecology does not involve aerial catches, as in the case of the great tit and the tawny owl (Redpath, 1995; Naef-Daenzer et al., 2000; Pagani-Núñez et al., 2011). Interestingly, both sedentary species showed an even distribution for ^{210}Pb activities among primary feathers. Results from this study reveal that adult migratory species may adsorb 20–30 times more ^{210}Pb as compared to non-migratory species or juvenile individuals, most likely due to the contact time between feathers and air. Pb-210 concentrations in feathers are directly related to the time the bird spends in flight.

Several parameters may influence the adsorption of ^{210}Pb in bird feathers aside from the location of feathers on the body of the bird, i.e., whether they are on the wings (remiges) or the tail (rectrices). Characteristics such as feather age, the moulting pattern (Dauwe et al., 2003; Jaspers et al., 2004), or the specific surface area of feathers are also relevant aspects to consider in understanding how ^{210}Pb is adsorbed in feathers from interaction with air. For instance, low concentrations of ^{210}Pb in feathers of migrating adults could indicate that the bird has recently moulted. Regarding surface area, it should be noted that results of this study are normalized by weight ($Bq \cdot kg^{-1}$), which does not necessarily correspond to the surface area of the feather in contact with the atmosphere and may depend on both the specimen and the species studied. Additionally, whether the bird is a gliding (common swift; Lentink et al., 2007) or a flapping species (great tit or tawny owl; Gosler, 1993; Martin, 2022), and the time that the bird spends in flight, may also be reflected in the concentrations of ^{210}Pb in feathers. Variation in the activity of ^{210}Pb in the air masses through which the birds fly also affects the activities found in bird feathers. These activities are influenced by numerous factors, including atmospheric pressure, altitude and ^{222}Rn diffusion rates from the Earth's surface, which differs significantly depending on the environment, e.g., marine vs terrestrial, sites with different geologies or different snow coverage, etc. (Piliposian and Appleby, 2003; Baskaran, 2011). Pb-210 concentrations in bird feathers could therefore provide information on the migration route (e.g., whether birds migrate over land or ocean, flight altitude, etc.).

The patterns observed in analysed feathers suggest that ^{210}Pb could be potentially used as a tracer of bird flight times given that: i) Juvenile common swift individuals do not have significant concentrations of ^{210}Pb as compared to adult specimens; ii) The highest ^{210}Pb concentrations are found in the primary feathers, those most in contact with air; iii) Migratory species showed much higher concentrations of ^{210}Pb in their primaries as compared to sedentary species; and iv) Higher concentrations found in the anterior vane of primary feathers as compared to the posterior vane and the rachis, confirms that ^{210}Pb is not accumulated by ingestion. The initial hypothesis on higher ^{210}Pb concentrations being found in feathers which have higher interaction with air is thus corroborated by the analysis results. However, complementary studies should be carried out to further confirm the applicability of ^{210}Pb in bird feathers as a tracer of age and flight times. Studies analysing primary feathers of a wider set of individuals, the study of different species that follow the same migratory routes, examination of different migratory routes for the same species, the combination of ^{210}Pb with other techniques applied to bird migration such as equipping birds with GLS/accelerometers, or the use of stable isotopes, would contribute to a better understanding of the application of naturally occurring radioactive isotopes to the study of bird migration.

5. Conclusions and recommendations

Analyses revealed for the first time concentration and distribution of naturally occurring ^{210}Pb in bird feathers in migratory and sedentary species for both adult and juvenile individuals. Results indicate that adsorption of ^{210}Pb in bird feathers is directly related to the interaction of feathers with air, and thus suggests that ^{210}Pb could be used as a potential tracer of age and bird flight times. More research on the adsorption pattern of ^{210}Pb in relation to the sequence of moulting in primary feathers of migratory adult individuals is recommended to further understand the use of this radioisotope to determine bird flight times. Obtaining additional information on the ^{210}Pb content by feather surface area ($Bq \cdot cm^{-2}$) could also facilitate refining relationships between ^{210}Pb and flight times of birds.

CRediT authorship contribution statement

Sara Fraixedas: Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Data curation. **Alba Riera:** Writing – review & editing, Formal analysis. **Carles Barriocanal:** Writing – review & editing, Methodology, Investigation. **Irene Alorda-Montiel:** Writing – review & editing, Visualization, Formal analysis. **Javier Quesada:** Writing – review & editing, Investigation, Funding acquisition. **Valentí Rodellas:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Jordi Garcia-Orellana:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

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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