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Published in:
Royal Society of London. Proceedings B. Biological Sciences

DOI:
10.1098/rspb.2000.0964

Published: 2000-01-01

Link to publication

Citation for published version (APA):

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Stable isotopes examined across a migratory divide in Scandinavian willow warblers (Phylloscopus trochilus trochilus and Phylloscopus trochilus acredula) reflect their African winter quarters

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The C and N isotopes of feathers from two subspecies of willow warblers (Phylloscopus trochilus trochilus and Phylloscopus trochilus acredula) are isotopically distinct. Our analysis of 138 adult males from 14 sites distributed across Sweden shows that the mean δ15N and δ13C values of subspecies acredula (from latitudes above 63°N) were significantly higher than the mean δ15N and δ13C values of subspecies trochilus (from latitudes below 61°N). The analysed willow warbler feathers had been moulted in the winter quarters and the observed isotopic signatures should thus reflect the isotopic pattern of food assimilated in Africa. The isotopic data observed in Sweden match the cline in morphology, both showing abrupt changes around 62° N. This result agrees with data from ringing recoveries indicating that the two subspecies occupy geographically and isotopically distinct wintering grounds in Africa. Our isotopic data suggest that analysis of stable isotopes of C and N is a promising method to track wintering quarters of European birds that migrate to Africa.

Keywords: stable isotopes; nitrogen isotopes; carbon isotopes; migratory birds; hybrid zone; Phylloscopus trochilus

1. INTRODUCTION

Linking breeding and winter quarters of long-distance migratory bird populations has been notoriously difficult, and relatively little is known about whether these populations mix or remain separated on their winter grounds. The traditional method to identify migratory routes and wintering areas of migratory birds has until recently relied exclusively upon analyses of recoveries of ringed birds. Despite a full century of ringing, we only have a fragmented picture of the winter ranges of most long-distance migratory bird species, mainly because of the low probability of obtaining intercontinental ringing recoveries (one out of 10^3-10^5 for most small birds). More recent methods, such as orientation experiments using Emlen funnels (Emlen & Emlen 1966) and satellite tracking (ARGOS 1994), will be of much help in revealing migratory directions of local populations, but these techniques are time laborious and expensive, which seriously limits collection of data sets covering larger regions. An alternative and novel approach is to use stable isotope compositions of animal tissues to track migratory patterns. Such a method has recently been applied to neotropical migrant birds (Chamberlain et al. 1997; Holson & Wassenaar 1997; Marra et al. 1998), monarch butterflies (Wassenaar & Hobson 1998), Atlantic salmon (Kennedy et al. 1997; Harrington et al. 1998) and African elephants (Van der Merwe et al. 1990; Vogel et al. 1990; Koch et al. 1995).

In this study, we apply this isotopic approach to two subspecies of willow warblers (Phylloscopus trochilus trochilus and Phylloscopus trochilus acredula) that are known to have different migratory routes and occupy geographically distinct winter quarters. A migratory divide is a region in which two populations showing different migratory direction meet; and ringing recoveries of willow warblers in Europe have demonstrated a migratory divide latitudinally in central Scandinavia (Hedenstrom & Petterson 1984, 1987). In autumn, birds in southern Scandinavia (trochilus) migrate south-west, whereas birds in northern Scandinavia (acredula) migrate south-east, both heading towards Africa. The available ringing recoveries (figure 1) suggest these birds occupy distinct areas of Africa in the winter. Such differences in migratory direction and migratory distance most likely reflect genetic differences (Berthold 1996; Hellbig 1996). Members of both subspecies start moultng all their flight feathers on their African winter grounds in December or early January (Underhill et al. 1992). Hence, we test the hypothesis that the isotopic composition of bird feathers collected in the breeding grounds should show a change across the migratory divide between the two subspecies of willow warblers.

Herein, we show that the N and C isotopes of feathers from the two subspecies of willow warblers change abruptly at the presumed location of the migratory divide, i.e. the location for the change in morphology and coloration (Bensch et al. 1999). This result most likely reflects the fact that trochilus and acredula occupy different areas in Africa when replacing their feathers. The results from this study provide supporting evidence for the use of stable isotopes for tracking migratory patterns of birds in general. In addition, the significantly different N and C isotope composition recorded in willow warbler feathers moulted in west and east Africa opens new avenues of research aimed at disentangling migratory routes and wintering areas of Palaearctic–African migratory birds.
2. METHODS

(a) The study species

In addition to exhibiting a migratory divide we found willow warblers suitable to study for four additional reasons. First, willow warblers moult all their flight feathers twice annually (in winter and summer) (Underhill et al. 1990, 1992; Hobson & Clark 1992). Different primary feathers from the same bird can have different isotopic values reflecting change in diet during growth of individual primaries (Thompson & Furness 1995; Bearhop et al. 1999). To avoid these possible complications all samples in this study were from the innermost primary feather on the left wing. In addition, not all willow warblers moult their flight feathers during the winter (Ginn & Mellville 1983). In these analyses we therefore only included feathers from birds in fresh plumage (>95% of examined birds), which apparently had undertaken a complete moult prior to spring migration. We analysed feathers from 138 males representing 14 sites distributed across Sweden for $^{15}\text{N}$ and $^{13}\text{C}$ values (table 1). It is also important to note that the $\text{N}$ and $\text{C}$ isotope ratios of feather keratin remain fixed after growth (Mizutani et al. 1999). Diﬀerent primary feathers from the same bird can have diﬀerent isotopic values reﬂecting change in diet during growth of individual primaries (Thompson & Furness 1995; Bearhop et al. 1999). Also shown is the ringing recoveries of birds ringed as either $\text{Ph. t. trochilus}$ (circles) or $\text{Ph. t. acredula}$ (squares).

(b) Analyses of ringing recoveries

We used the ringing recoveries reported to the Swedish Museum of Natural History between 1960 and 1998. To identify whether the ringing recoveries in Africa were representing $\text{Ph. t. trochilus}$ or $\text{Ph. t. acredula}$ we used the following criteria. Those birds ringed in Sweden south of 60°N either before 10 May (before the ﬁrst $\text{Ph. t. acredula}$ migrates through southern Sweden (Hedenström & Pettersson 1984)) or during June and July were identiﬁed as $\text{Ph. t. trochilus}$ ($n = 5$). Those birds ringed either north of 63°N, or after 1 September in southern Sweden (when the majority of $\text{Ph. t. trochilus}$ already have departed from Sweden (Hedenström & Pettersson 1984)) were identiﬁed as $\text{Ph. t. acredula}$ ($n = 12$). The subspecies identity of eight birds was ambiguous and therefore excluded from analyses.

(c) Data collection and analyses of stable isotopes

In May and June of 1996 and 1997, we sampled feathers of male willow warblers captured on their breeding territories in mist-nets with aid of song playback at 32 sites in Sweden between 55°N and 67°N (Bensch et al. 1999). In addition to the migratory divide we found willow warblers suitable to study for four additional reasons. First, willow warblers moult all their flight feathers twice annually (in winter and summer) (Underhill et al. 1990, 1992; Hobson & Clark 1992). Different primary feathers from the same bird can have different isotopic values reflecting change in diet during growth of individual primaries (Thompson & Furness 1995; Bearhop et al. 1999). To avoid these possible complications all samples in this study were from the innermost primary feather on the left wing. In addition, not all willow warblers moult their flight feathers during the winter (Ginn & Mellville 1983). In these analyses we therefore only included feathers from birds in fresh plumage (>95% of examined birds), which apparently had undertaken a complete moult prior to spring migration. We analysed feathers from 138 males representing 14 sites distributed across Sweden for $^{15}\text{N}$ and $^{13}\text{C}$ values (table 1). It is also important to note that the $\text{N}$ and $\text{C}$ isotope ratios of feather keratin remain fixed after growth (Mizutani et al. 1999). Diﬀerent primary feathers from the same bird can have diﬀerent isotopic values reﬂecting change in diet during growth of individual primaries (Thompson & Furness 1995; Bearhop et al. 1999). Also shown is the ringing recoveries of birds ringed as either $\text{Ph. t. trochilus}$ (circles) or $\text{Ph. t. acredula}$ (squares).
Table 1. N and C isotope compositions of willow warbler feathers from Sweden

<table>
<thead>
<tr>
<th>sample site</th>
<th>δ¹⁵N</th>
<th>δ¹³C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>s.e.</td>
</tr>
<tr>
<td>55° 42' N</td>
<td>13° 27' E</td>
<td>7–10 May 1996</td>
</tr>
<tr>
<td>56° 15' N</td>
<td>14° 00' E</td>
<td>15–17 May 1997</td>
</tr>
<tr>
<td>58° 19' N</td>
<td>14° 49' E</td>
<td>28–30 May 1997</td>
</tr>
<tr>
<td>59° 10' N</td>
<td>15° 25' E</td>
<td>12–17 May 1996</td>
</tr>
<tr>
<td>60° 24' N</td>
<td>17° 58' E</td>
<td>21–22 May 1996</td>
</tr>
<tr>
<td>61° 43' N</td>
<td>17° 25' E</td>
<td>26–27 May 1996</td>
</tr>
<tr>
<td>61° 53' N</td>
<td>12° 44' E</td>
<td>16–17 June 1996</td>
</tr>
<tr>
<td>62° 02' N</td>
<td>14° 03' E</td>
<td>8–10 June 1997</td>
</tr>
<tr>
<td>62° 28' N</td>
<td>17° 29' E</td>
<td>28–30 May 1996</td>
</tr>
<tr>
<td>63° 21' N</td>
<td>12° 33' E</td>
<td>10–11 June 1996</td>
</tr>
<tr>
<td>63° 29' N</td>
<td>19° 42' E</td>
<td>3–4 June 1996</td>
</tr>
<tr>
<td>65° 58' N</td>
<td>16° 07' E</td>
<td>6–8 June 1996</td>
</tr>
<tr>
<td>67° 13' N</td>
<td>20° 48' E</td>
<td>26–27 June 1997</td>
</tr>
</tbody>
</table>

+10.1 ± 0.27% (n = 48) and -19.9 ± 0.26% (n = 48), respectively. In contrast, the mean δ¹⁵N and δ¹³C values of subspecies trochilus from latitudes below 61° N were both lower (+7.3 ± 0.21%o, n = 30 and -21.5 ± 0.29%o, n = 50, respectively). Differences between the mean values of δ¹⁵N and δ¹³C for the two subspecies were significant (ANOVA: p < 0.001 for both δ¹⁵N and δ¹³C). Within the contact zone, between latitude 61° N and 63° N, the mean δ¹⁵N value was +8.7 ± 0.27% (n = 40) and mean δ¹³C value was -21.2 ± 0.21% (n = 40) (figure 2). There was no effect of date of sampling (table 1) for either C (F₁,₁₄₃ = 0.7, p = 0.4) or N (F₁,₁₄₃ = 0.8, p = 0.4) in the ANOVA testing for differences between regions. Similarly, there was no effect of sampling site on δ¹⁵N. Second, the N and C isotopic data match the cline in morphology for willow warblers in central Sweden (figure 3). Recent work (Bensch et al. 1999) has shown differences in size and plumage coloration in willow warblers across the migratory divide in central Scandinavia. The relationship between mean (± s.e.) and latitude for two morphological traits (wing length n = 32 sites, and body mass n = 32), and C and N isotope compositions of willow warblers captured in Sweden is shown in figure 3. The lines in figure 3 indicate the average values for the populations south and north of the identified transition zone (61°–63° N), respectively. Note that the differences in δ¹⁵N and δ¹³C values occur at the same latitudes as the changes in morphological traits. Because the northern birds are larger than the southern birds one could argue that the differences observed in isotopic signatures were a result of size-related food preferences. However, most of the size variation (>80%) is within and not between the subspecies, and there was no significant effect of size (wing length or body mass) on δ¹⁵N or δ¹³C in the ANOVA testing for differences between regions (all p > 0.05).

Based on morphological features, Bensch et al. (1999) estimated the transition zone between northern and southern willow warblers to be less than 350 km. Our isotopic data show a geographical change at least as distinct as for the morphological traits. These results suggest that the isotopic pattern observed in Scandinavia reflects distinctly different African winter quarters of the two subspecies of Scandinavian willow warblers.

4. DISCUSSION

The willow warbler has a winter range covering most of sub-Saharan Africa, and is found mainly in savannah and forest clearings, avoiding closed evergreen forests (Cramp 1992). The few ringing recoveries suggest that trochilus migrates to western Africa and acredula migrates to central-eastern Africa (figure 1). However, despite the ringing of 715 000 willow warblers in Sweden up to 1995 (Stolt et al. 1997), the few ringing recoveries accumulated so far have not enabled us to locate the position and width of the migratory divide.
We found that the C and N isotopes of two subspecies of willow warblers (*acredula* and *trochilus*) changed abruptly at the same latitude (62°N) as the change in morphological traits. It has been shown that: (i) the N and C isotopes of feathers reflect the diet and local environmental conditions were the tissues were grown (Mizutani et al. 1990, 1992; Hobson & Clark 1992); and (ii) with the exception of hydrogen isotopes (Chamberlain et al. 1997) the isotopic composition of feather keratin is fixed after growth. Thus, the differences in the $^{15}$N and $^{13}$C values for *acredula* and *trochilus* most likely result from these two subspecies of willow warblers wintering in isotopically distinct areas in Africa, a result which is consistent with rare ringing recoveries mentioned above.

The C and N isotope values of animals are strongly influenced by diet and trophic structure (DeNiro & Epstein 1978, 1981; Minagawa & Wada 1984; Wada et al. 1987; Mizutani et al. 1990, 1992; Hobson & Clark 1992). During the winter season, willow warblers are primarily insectivorous but the exact trophic structure of the two subspecies is unknown. It is therefore possible that *trochilus* and *acredula* occupy the same geographical region (although this is not supported by ringing recoveries) and the different isotopic signatures reflect intrinsic differences in diet between the two subspecies. We consider this explanation unlikely for the following reasons. First, body size did not correlate with isotopic signatures. Such a correlation would be expected if larger birds were feeding on larger prey types containing different isotope ratios. The lack of a correlation between body size and isotope ratios and the fact that most of the size variation occurs within rather than between subspecies suggest that any difference in trophic structure is not the cause of the isotopic difference between *trochilus* and *acredula*. Second, we only included males in the analyses so possible differences in prey selection between the sexes (Nystrom 1991) cannot have biased the result. Third, we analysed the same feather, the innermost primary, in all birds. This is the first feather the birds are replacing in their moult, and because of the small wing gap at this stage of moult (Bensch & Grahn 1993), they probably can keep their flight performance and usual feeding technique when growing this feather (Hedenstrom 1998). In addition, start of moult varies only moderately in Africa; early December in Guinea-Bissau, late December in South Africa and early January in Uganda (Underhill et al. 1992). Hence, most of the analysed feathers should have been replaced within the same month-long period so that it is unlikely that the isotopic differences between *trochilus* and *acredula* reflect differences in diet at different moulting times.

We, therefore, suggest that the differences between isotopic ratios of *trochilus* and *acredula* primarily result from the two subspecies wintering in isotopically distinct areas. However, without regional isotopic maps of feathers from willow warblers from Africa it is impossible to know exactly where in Africa the two subspecies winter. Since local environmental conditions strongly influence N and C isotopic values it is possible to place constraints on where the two subspecies of willow warblers winter. As mentioned above, willow warblers in Africa are found mainly in savannah and forest clearings (Cramp 1992). The C isotope values of willow warbler feathers are indicative of an ecosystem dominated by C3 African trees, shrubs and grasses (approximately 27% (Smith & Epstein 1971; Koch et al. 1995)). In addition, the

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**Figure 3.** The relationship between mean (± s.e.) and latitude for two morphological traits, and C and N isotope compositions of willow warblers captured in Sweden. (a) Wing length (n = 32 sites), (b) body mass (n = 32), (c) $\delta^{15}$N (n = 14) and (d) $\delta^{13}$C (n = 14). Mean values for wing length and body size are based on measurements of ten to 20 males per site. The lines indicate the average values for the populations south and north of the identified transition zone (61–63°N), respectively. Contact-zone willow warblers are presented by open diamonds; subspecies *acredula* by squares, and subspecies *trochilus* by circles.
relatively high δ¹⁵N values of willow warblers are consistent with a trophic structure originating at base level African plants (δ¹⁵N of approximately 5 to 3‰) in areas with relatively low mean annual precipitation; less than 500 mm per year (Heaton 1987; Johnson et al. 1997). Our isotopic data on willow warblers are, therefore, consistent with the observations that the dominant habitat of willow warblers in Africa is savannah and forest clearings.

We suggest that the higher δ¹⁵N and δ¹³C values of subspecies trochilus compared with subspecies acredula reflect the fact that acredula winters in an area (East Africa) with a more arid climate and a higher ratio of C₄–C₃ plants. This argument is based on the following two reasons. First, studies have shown that elevated δ¹⁵N values of plant (Heaton 1987) and animal tissues (Van der Merwe et al. 1990; Heaton et al. 1986; Sealy et al. 1987; Ambrose 1991; Ambrose & DeNiro 1989; Johnson et al. 1997) in Africa occur in areas with relatively low rainfall. This increase in δ¹⁵N values is presumably the result of δ¹⁵N enrichment of soil N in dry soils due to higher rates of N loss (Shearer et al. 1978) and propagation of this N isotope signal through the food web. The elevated δ¹⁵N/acredula is consistent with these N isotope studies. Second, the relatively high δ¹³C in animal tissues reflects, in part, the increased abundance of C₄ relative to C₃ plants in the ecosystem because C₄ plants have higher δ¹³C values than C₃ plants (mean approximately −13‰) than C₃ plants (mean approximately −27‰) (Smith & Epstein 1971). In addition, C₃ plants have higher δ¹³C values in water-limited habitats (Ehleringer & Cooper 1988), which would also result in elevated δ¹³C of animal tissues in arid areas. We, therefore, speculate that the elevated δ¹³C values observed in acredula reflect an increase in the ratio of C₄–C₃ plants in a water-limited environment.

Our interpretation is consistent with regional isotopic studies of elephant bone collagen in Africa (Van der Merwe et al. 1990; Vogel et al. 1990; Koch et al. 1995). In these isotopic studies it was shown that individual populations of African elephants had distinct δ¹⁵N and δ¹³C values (Van der Merwe et al. 1990; Vogel et al. 1990), although there was considerable variability within a given population due to local environmental effects (Koch et al. 1995). In general, east and south African elephants had higher δ¹³C values and similar or higher δ¹⁵N values than west African elephants (Koch et al. 1995, fig. 4). These authors (Van der Merwe et al. 1990; Vogel et al. 1990) also attributed the high δ¹⁵N and δ¹³C values to increased aridity and relative abundance of C₄ plants.

Our isotopic data agree with the results from ringing recoveries that trochilus and acredula winter in distinct areas in Africa. However, for birds within the contact zone (those birds between latitudes 61°N and 63°N) in central Sweden it is unclear from the isotopic data whether these birds represent a mix of the two subspecies or whether these birds winter in a different area in Africa. The C isotopic ratios (figures 2 and 3; table 1) suggest that local sites consist either of pure trochilus (three sites) or pure acredula birds (one site). In contrast, mean N isotopic ratios within these local sites were intermediate between those of trochilus and acredula, with the mean δ¹⁵N value differing significantly from the mean of either subspecies (p < 0.05). Hence, the N isotopic ratios suggest that the sites in the contact zone either consist of a mix of birds from the two subspecies, or that the birds in the contact zone winter in an area with a distinct N isotopic signature. The former explanation is consistent with data on morphology, which indicate the presence of linkage disequilibrium between size and coloration within the contact zone (Bensch et al. 1999). This explanation is also consistent with the hypothesis that there is a continuous influx into the contact zone of birds from the north (which are larger and have grey-brown plumage), and birds from the south (which are smaller and have green-yellow plumage) (Bensch et al. 1999).

Thus, from our isotopic data alone it remains unclear which migratory route is followed by contact-zone willow warblers. Further research using stable isotope signatures from willow warblers breeding in this contact zone will allow us to test whether birds mate randomly or assortatively with respect to migratory direction and winter location (as measured by isotopic signatures). For example, contact-zone birds that show intermediate isotope signatures (supposed hybrids) can be used in orientation experiments directly testing whether they take up an intermediate course of migration in autumn.

5. CONCLUSIONS

In conclusion, the strong correlation between morphological features and stable isotopic ratios of two subspecies of willow warblers, which migrate to geographically distinct areas in Africa, supports the use of stable isotopes as a method for tracking migratory patterns of birds (Chamberlain et al. 1997; Hobson & Wassenaar 1997). We, therefore, suggest that the significantly different N and C isotope composition recorded in willow warbler feathers moulted in West and East Africa, respectively, opens new avenues of research aimed at disentangling migratory routes and wintering areas of Palaearctic–African migratory birds in general. The addition of other isotopic ratios, such as δD and δ¹⁸Sr, which have been used elsewhere (Chamberlain et al. 1997; Hobson & Wassenaar 1997), when combined with N and C will allow further discrimination of wintering ranges of bird populations, and reveal the potential problem of high isotopic variability due to local ecological shifts (Koch et al. 1995). An important task will be to collect data enabling the construction of regional isotopic maps of feather keratin for migratory species in their African wintering grounds, like those under construction for neotropical birds in North America (Chamberlain et al. 1997; Hobson & Wassenaar 1997).

This research was supported by Fredrick Hall Professor funds (to C.P.C.), Uddenberg Nordingska Stiftelsen and the Swedish Natural Science Research Council (to S.B. and S.Ð.A.). We thank Paul Koch and Richard Holmes for their thoughtful reviews.

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