

Visual counts, bioacoustics and RADAR: three methods to study waterfowl prenuptial migration in Southern France

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Abstract

Visual counts, bioacoustics and RADAR: three methods to study waterfowl prenuptial migration in Southern France.— This study comes from four years (2006–2009) of monitoring on two sites during the prenuptial migration. On each site, a monitoring of 24 hours per each 10-day period from the second 10-day period of January (J2), though February (F1–F3) and March (M1–M3), up to the first 10-day period of April (A1). Monitoring was carried out by RADAR (FURUNO FAR2127), associated with nocturnal bioacoustics recordings, and visual censuses on the same areas. The monitoring effort was considerable: visual counts carried out represent 282 counts–sites ($n = 262,030$ ducks counted), bioacoustics detected 9,573 calls during 814 hours of nocturnal recording and RADAR recorded 67,368 echoes on a set of 2,128 hours of monitoring. Visual counts showed a decline in the number of birds from late January/early February. Two patterns were observed with the nocturnal recordings with a maximum or a minimum of the value of bioacoustics index on F2 and F3, depending on the years. RADAR, the most relevant method for tracking of bird movements at a population level, identified two different abundance peaks using variables 'flight altitude > 400 m' and 'flight direction towards north–east/south–east', considered as characteristics of the prenuptial migration. The first peak was detected during F1 on Site 1 only in 2007 (once every four years) and during F2 on Site 2 only in 2006 (once every four years). A second peak with a higher number of echoes was recorded on M1 (Site 1) and on M2 (Site 2). Although all methods may suffer from different biases, the combination of two new technologies complementary to visual counts provided reliable and updated data for waterfowl migration in the Mediterranean area.

Key words: Prenuptial migration, Waterfowl, Counts, Bioacoustics, RADAR.

Resumen

Conteos visuales, bioacústica y RADAR: tres métodos para estudiar la migración prenupcial de aves acuáticas en el sur de Francia.— Este estudio es el resultado de cuatro años de monitorización (2006–2009) en dos lugares durante la migración prenupcial. En cada uno, se llevó a cabo un seguimiento de 24 horas, durante periodos de 10 días, a lo largo de la segunda década de enero (J2), el mes de febrero (F1–F3), marzo (M1–M3) y la primera década de abril (A1). La migración se monitorizó mediante RADAR (FURUNO FAR2127), asociado con grabaciones bioacústicas nocturnas, y censos visuales en las mismas áreas. El esfuerzo de muestreo fue considerable: los conteos visuales totalizaron 282 conteos–sitios ($n = 262.030$ patos contados), mediante bioacústica se obtuvieron 9.573 vocalizaciones en 814 horas de grabación nocturna y mediante RADAR se registraron 67.368 ecos durante 2.128 horas de vigilancia. Los censos visuales muestran una disminución del número de aves a finales de enero/principios de febrero. Los registros nocturnos presentan un máximo o mínimo del índice bioacústico en F2 y F3 función del año. El RADAR, el mejor método para estudiar los movimientos de aves a nivel de población, identificó dos picos de abundancia diferentes, utilizando las variables "altura de vuelo > 400m" y "dirección de vuelo hacia noreste/sureste" consideradas como características de la migración prenupcial. El primer pico se detectó en F1 en el Sitio 1 sólo en el 2007 (un año de cada cuatro) y en F2 en el Sitio 2 sólo en el 2006 (un año de cada cuatro). Un segundo pico, de mayor intensidad, se detectó en M1 (Sitio 1) y en M2 (Sitio 2). Aunque todos los métodos considerados pueden tener sesgos, el uso de dos nuevas tecnologías en combinación con los conteos visuales, nos ha permitido obtener datos fiables y actuales sobre la migración de aves acuáticas en el área mediterránea.

Palabras clave: Migración prenupcial, Aves acuáticas, Conteos, Bioacústica, RADAR.

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Introduction

Bird migration is an annual journey performed between breeding and wintering areas. We distinguish postnuptial migration (after breeding heading wintering sites) and prenuptial migration (before breeding coming back to nesting sites). The spring migration (prenuptial), the aim of this study, is characterized by flight altitudes higher than the autumn migration (postnuptial) (Elkins, 1996; Bruderer, 1997), and is often carried out more quickly (Arzel et al., 2006) to reach nesting sites sooner and to reproduce in the best conditions (Gordo, 2007). In France, a major route of prenuptial migration crosses the Mediterranean arc (MNHN & ONC, 1989; Dubois & Rousseau, 2005) (fig. 1). Migratory waterfowl come from Spain or Africa and head for the north/north-east direction. Some follow secondary routes and head for the east and north-east direction (Laty, 1979; ONFSH, 2004; ORNIS, 2008). The waterfowl movements are very complex, especially between their wintering sites and their breeding sites (MNHN & ONC, 1989). It is often difficult to distinguish between the local movements and the migratory flights. Moreover, according to the European Directive 2009/147/CE, member states should not hunt migratory bird species 'during their period of reproduction or during their return to their rearing grounds'. Therefore, thorough knowledge of the timing of the prenuptial migration is crucial for the conservation of migratory bird species. The chronology of waterfowl prenuptial migration in France is a subject treated by many authors on a national scale but only with methods such as visual counts or ringing (Fouque et al., 1997; ONFSH, 2004; Guillemain et al., 2006). For this reason we selected two recent technologies for this study: RADAR and bioacoustics. Thus, this study is innovative because it is the first time these three complementary methods are used simultaneously. The aim of this study, in a context of conservation biology, is not to quantify bird migration but rather to determine the period from which the migration variables used and defined in this paper are fulfilled, in the French Mediterranean area.

Material and methods

This study was carried out on two sites in Southern France, located on the main axis of waterfowl spring migration (fig. 1). The RADAR was located at Fleury d'Aude (Site 1) ($43^{\circ} 12.301$ N, $3^{\circ} 11.525$ E), within a wetland situated between the Mediterranean sea and a large scrubland associated to wine-producing areas, near the 'Pissevache pond', not previously reported as a national or international wintering site for ducks (Deceuninck & Fouque, 2010). As for Site 2, the RADAR was located at Saintes Maries de la Mer in the Camargue ($43^{\circ} 29.842$ N, $4^{\circ} 27.032$ E), between two main water bodies ('Consécanière pond' and 'Imperial pond'), three kilometers to the north of the Mediterranean sea, within a wetland of international interest for bird conservation, and the most important wintering area for ducks in the French Mediterranean area (Deceuninck & Fouque, 2010).

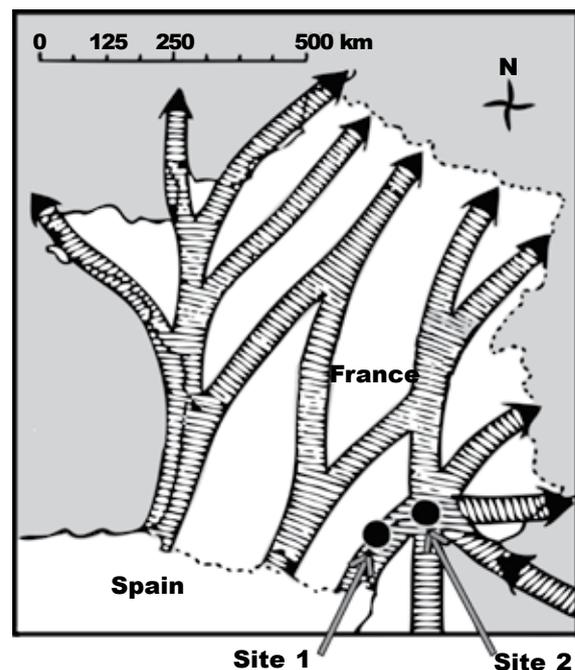


Fig. 1. Migratory corridors of prenuptial migration in France with the two study sites (modified from Laty in MNHN/ONC, 1989).

Fig. 1. Corredores de migración prenuptial en Francia con los dos sitios de estudio (modificado de Laty en MNHN/ONC, 1989).

The monitoring was conducted on each site, and for each 10-day period, from the second 10-day period of January to the first 10-day period of April, from 2006 to 2009. Thus, in this paper, each 10-day period of each month is named with the first letter of the month considered and the number of the corresponding 10-day period (e.g. J2 for the second 10-day period in January). During each 10-day period, RADAR tracking took place for 24 hours, from noon to noon, and the bioacoustics station worked from 8 p.m. to 8 a.m.

The visual counts were carried out each morning following RADAR monitoring on various ponds within the same area by one or two observers with a telescope (fig. 2). Counting sites were chosen in order to reflect the best typical duck habitats, and the survey tried to cover all the open water of the pond considered. On Site 1, four ponds were counted on each 10-day period (except for A1 in 2007) during the four years of the study: 'Estagnol pond', 80 ha, two counting points; 'Vic la Gardiole pond', 1,255 ha, but only 520 ha counted with five points; 'la Castillone pond', 75 ha, one counting point and 'Saint Marcel pond', 38 ha, two counting points. In 2008 and 2009, an additional pond was counted: 'Vendres pond',

1,800 ha, two counting points. Near Site 2, three ponds were counted: 'Consécanière pond', 1,700 ha, two counting points; 'Mas de Tamaris pond', 53 ha, one counting point, and 'Mas de l'Ange pond', 20 ha, one counting point. The large 'Consécanière pond' is a protected area with no hunting but it is surrounded by many ponds where hunting is allowed, particularly at southern, western and northern points. Hunting was allowed in the remaining wetlands of our sample, such as 'Mas de l'Ange' and 'Mas de Tamaris' ponds. Not all counting points were sampled in every 10-day period. Thus, 'Consécanière pond' was not counted on J2 and A1 in 2006 or F2 in 2007. 'Mas de Tamaris pond' could not be counted on J2, F1 and A1 in 2007 and was dried up in M3 and A1 in 2007 and since M1 in 2008. Similarly, 'Mas de l'Ange pond' was not counted on J2 and A1 in 2006 and was dried up since M2 in 2007 and since F2 in 2008. All these areas are known to be wintering sites (Deceuninck & Fouque, 2010) for ducks but the number of wintering birds is much lower on the Site 1 than in the Camargue (Site 2). Others censuses were performed on two complementary sites ('Canet pond', 1,000 ha, 12 counting points and 'Villeneuve de la Raho pond', 225 ha, 10 counting points) located in the Eastern Pyrenees from 2006 to 2009. These counting sites consist of isolated large ponds, and are known to be wintering sites for ducks (Deceuninck & Fouque, 2010). All counting points at each site were the same throughout the four years of the study. All waterfowl species were counted, but this study focused only on following Anatidae species: mallard (*Anas platyrhynchos*), teal (*Anas crecca*), gadwall (*Anas strepera*), wigeon (*Anas penelope*), pintail (*Anas acuta*), garganey (*Anas querquedula*), shoveller (*Anas clypeata*), common shelduck (*Tadorna tadorna*), red-crested pochard (*Netta rufina*), common pochard (*Aythya ferina*), tufted duck (*Aythya fuligula*), and greater scaup (*Aythya marila*).

Bioacoustics recordings were performed on RADAR locations using a bioacoustics station consisting of a microphone (Telinga pro PIP 4, 40 Hz–18 MHz) with a theoretical limit detection of 1000 meters, a parabolic reflector, and a sound numeric recorder (Sony MiniDisc). Recordings were heard and analyzed by a specialized operator. All calls (with the identification of the species when it was possible) and bird movements (such as a characteristic wing noise of a duck) were noted with the time of recording. Only species mentioned previously were considered in this work.

Finally, we used a maritime RADAR (FURUNO FAR-2127 BlackBox (X-Band, 9,410 ± 30 MHz), 25 kW power) with an antenna (XN-24AF) of 2.40 m length. The antenna can be elevated to a height of 12 m using a hydraulic platform for a better detection of the targets. The RADAR is connected to a mobile laboratory (camping-car) fitted out with a control screen, a GPS, and a console to adjust the RADAR settings (Seaman, Gain, Range, etc.). Data were recorded using the software RecordRADAR, v1.2 (Pégase Instrumentation) in a computer. The reflectivity of RADAR waves, on the water surface, is limited, or even absent. For this reason the RADAR was located near a large pond on both sites

in order to avoid the ground clutter. Thus, the echo reading was facilitated throughout the reading line (horizontal position). In vertical position, targets were detected under an altitude of 100 m and over 3,000 m. However, a blind sector of about 50 m around the RADAR, in both positions, prevented any echo reading. Two positions were used for each hour of monitoring (10 minutes of recording in each position). Horizontal position detects and tracks flight directions. Thus, the RADAR was positioned facing the migration front (south–west), with a range of 3 km. For the notation, only echoes crossing an imaginary line perpendicular to the migration front (reading line) were considered for the directions (fig. 3). Therefore, the echoes directions were classified according to four classes: south–west/north–west (SWNW), north–west/north–east (NWNE), north–east/south–east (NESE) and south–east/south–west (SESW). Vertically, the RADAR detects flight altitudes, with a range of 1.5 km, and all the echoes were noted according to two classes that were determined 'a posteriori' after analysing data: below and above 400 m (< 400 m and > 400 m; see below and Results for a justification of this threshold). For each monitoring, RADAR settings were optimized (pulse s2, Gain = 60, Seaman ≥ 20) to detect, with a range between 1.5 km and 3 km, at least mid-sized birds.

Overall sampling effort was important: visual counts carried out represent 282 counts–sites (n = 262,030 birds counted), bioacoustics detected 9,573 contacts during 814 hours of nocturnal recording, and RADAR recorded 67,368 echoes on a set of 2,128 hours of monitoring.

As explained in the previous section, all ponds may not have been counted during every monitoring for several reasons (weather, pond dried up during the study, etc.). For this reason, the visual count results (analysed with STATISTICA 7.1 software) for each site are presented as the average number of Anatidae per pond counted with the associated standard deviation (fig. 4). Concerning the bioacoustics results, the number of contacts (calls or typical wing noises of ducks) was analyzed per workable hour according to 10-day periods for each year, called 'Bioacoustics index'. Mallards (*Anas platyrhynchos*) and common shelducks (*Tadorna tadorna*) were removed from the analysis because these species are mainly sedentary in the study areas (fig. 5, STATISTICA 7.1 software). The data were compared with a random distribution of the bioacoustics index for the nine 10-day periods studied (χ^2 test). Bonferroni intervals (Neu et al., 1974; Byers et al., 1984) were then calculated to identify 10-day periods that differed significantly from the others.

Anatidae species are mainly nocturnal migrants (Cramp & Simmons, 1977). Many studies performed in other countries have shown that migration starts about one hour after sunset and reaches a peak between the first and fourth hour of the night (Gauthreaux, 1971; Alerstam, 1976; Richardson, 1978; Laty, 1979; Bruderer, 1997; Zehnder et al., 2002; Bruderer, 2003). So as to avoid the local movement of ducks between their resting areas and their foraging areas (during

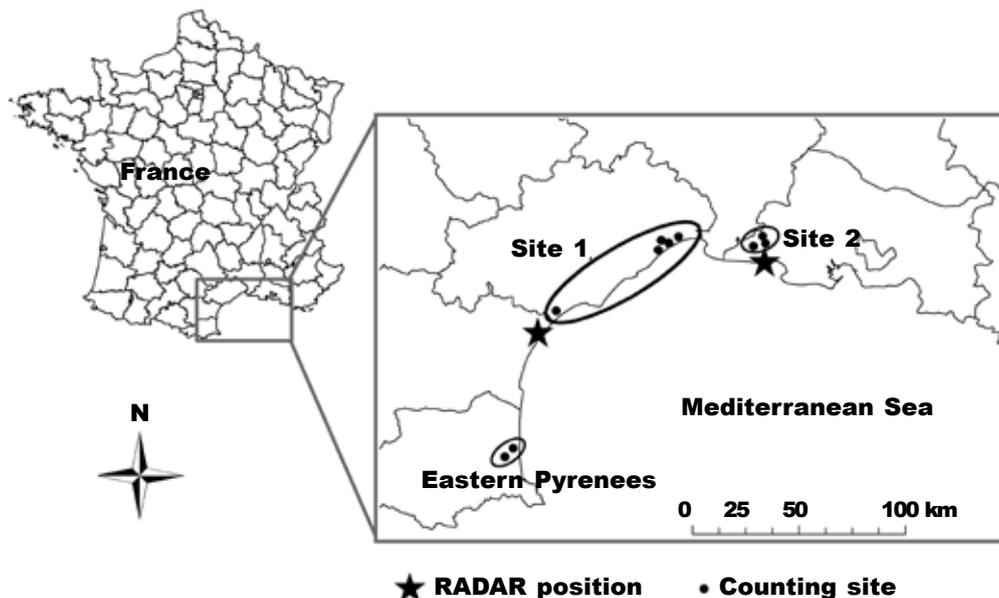


Fig. 2. Study areas with RADAR locations and counting sites.

Fig. 2. Zonas de estudio con las posiciones del RADAR y de los lugares de conteo.

the beginning and the end of the day) (Tamisier & Dehorter, 1999), only nocturnal values between 8 pm and 5 am were considered (both for bioacoustics and RADAR results).

RADAR results are first presented using the Migration Traffic Rate (MTR) (figs. 6, 7; STATISTICA 7.1 software), widely used in others studies (Lowery, 1951; Bruderer, 1971; Rivera & Bruderer, 1998; LPO/Biotope, 2008; Schmaljohann et al., 2008). MTR is defined as the number of echoes crossing a virtual line of fixed length (1 km) perpendicular to the flight direction within one hour. Therefore, the data recorded during ten minutes (for each antenna position) were converted to obtain a number of echoes per kilometer and per hour. A Principal Component Analysis (PCA) was then performed for data from each site (STATISTICA 7.1 software) in order to compare all the 10-day periods according to nocturnal flight direction and altitude variables (fig. 8). Finally, it is widely accepted that the main flight direction of migrant birds, during prenuptial migration in the study areas is towards the east and north east (Laty, 1979; ONFSH, 2004; ORNIS, 2008). Moreover, nocturnal migratory birds are known to fly at high altitudes during their migration (Kerlinger, 1995; Miller et al., 2005), and according to Newton (2008), the birds fly at low altitudes when they perform local movements. Thus, we assumed that the flight altitudes above 400 m could reflect migrant birds. We therefore considered two variables as characteristics of the prenuptial migration in this study: flight directions towards north-east/south-east (NESE) and flight altitudes above 400 m (> 400 m).

Results

Visual counts

On Site 1 (fig. 4), following a decrease in the number of birds until J3, the number of ducks seemed to increase from F1 (2008) or F2 (2006) to M1. In 2007

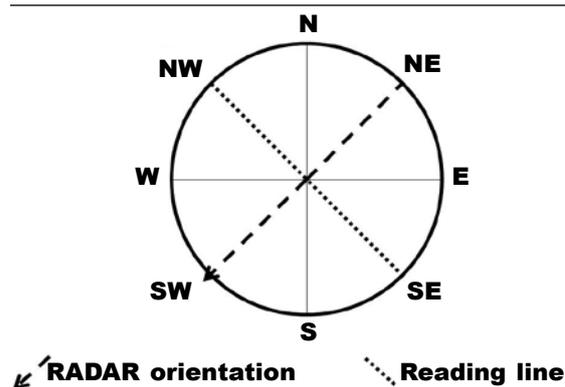
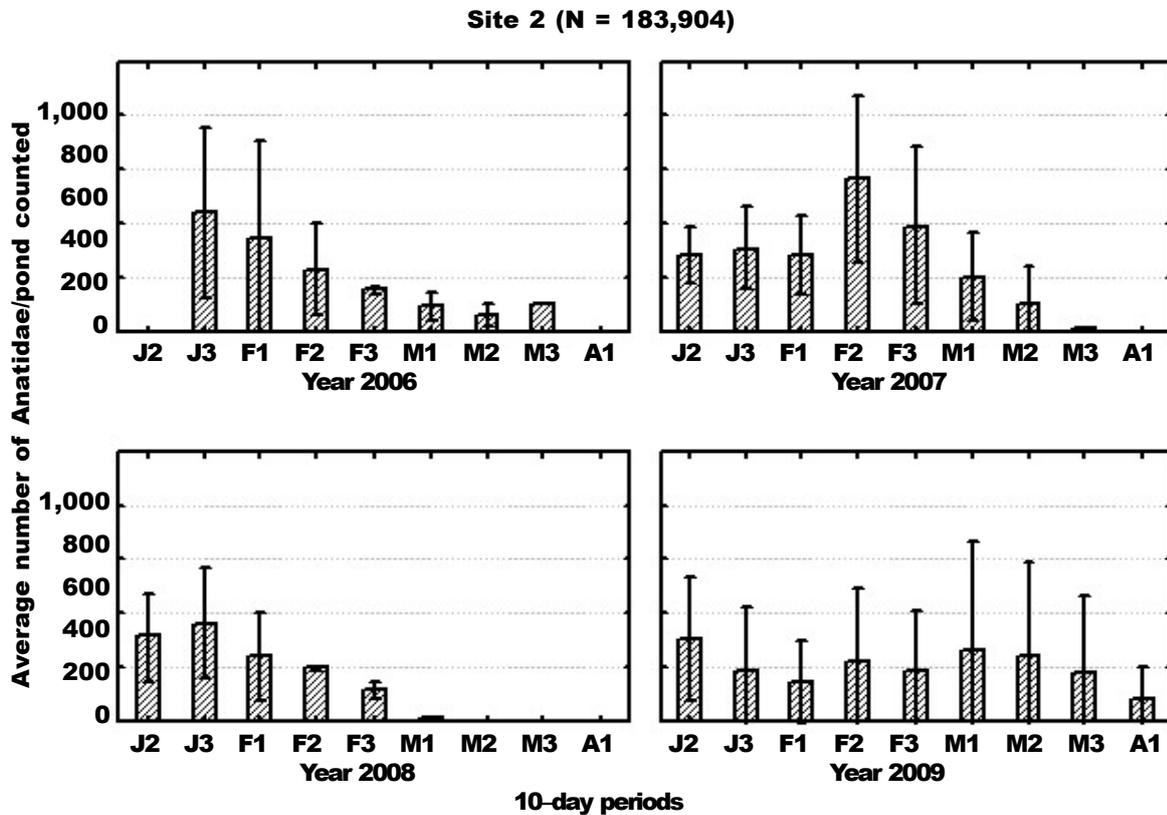
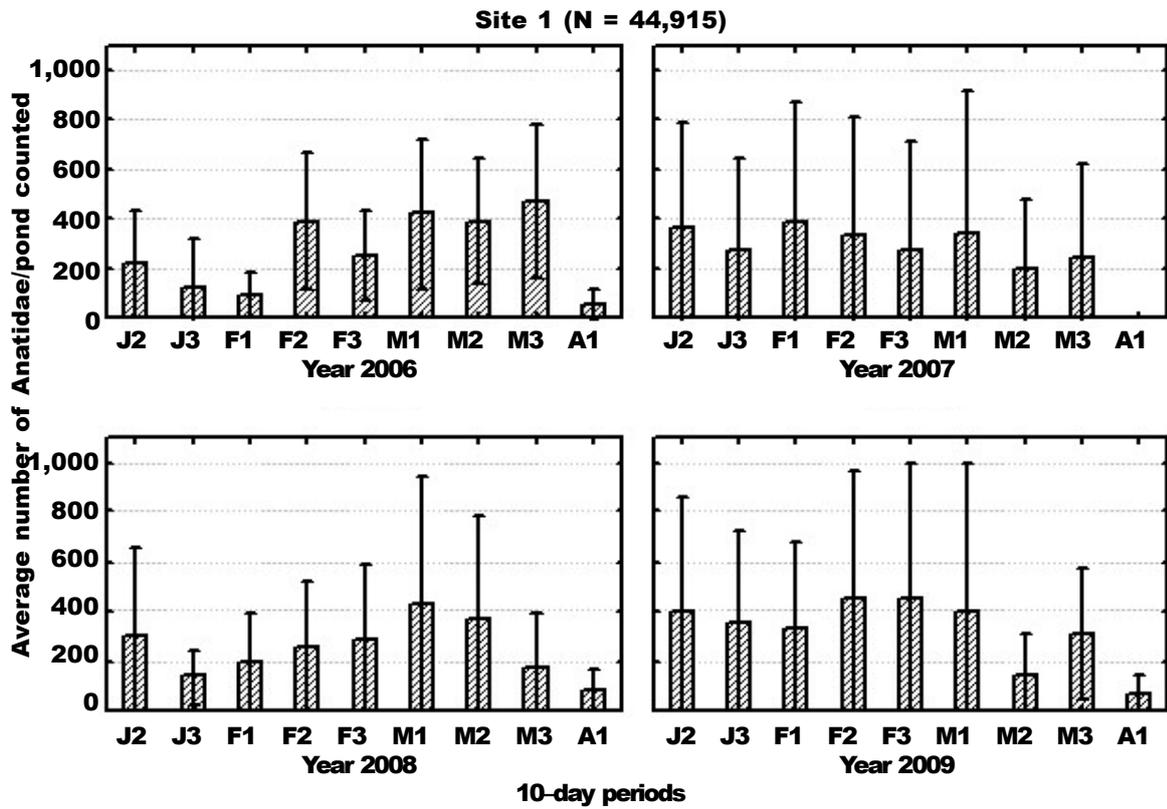


Fig. 3. Schematic illustration of the RADAR orientation and the reading line for the echoes notation in horizontal position.

Fig. 3. Ilustración esquemática de la orientación del RADAR y la línea de la lectura para la notación de los ecos en posición horizontal.



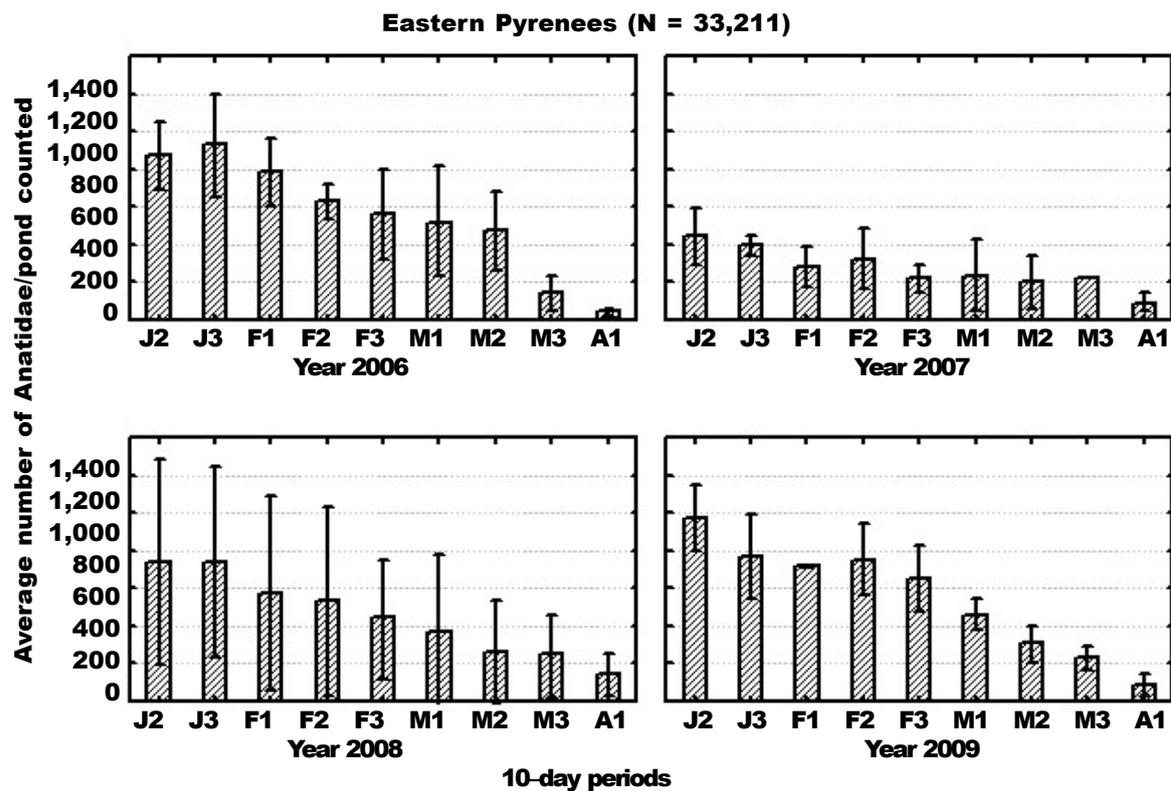


Fig. 4. Average number (\pm SD) of Anatidae per pond counted on Site 1, Site 2 and the Eastern Pyrenees sites, according to 10-day periods and years.

Fig. 4. Número medio (\pm DE) de Anatidae por estanque contados en el Sitio 1, el Sitio 2 y en los sitios de los Pireneos Orientales, según los periodos de diez días y los años.

and 2009, the number of ducks seemed to be relatively equivalent until M1. A marked drop was observed for each year of the study on A1. On Site 2 (fig. 4), a similar trend was observed in 2006 and in 2008, with a decrease in bird numbers since J2 until M2. In 2007, the number of ducks seems to be similar from J3 to F1. An increase was observed on F2 before an important decrease until A1. In 2009, a low decrease in the number of birds was observed from J2 to F1. Then, increases were observed on F2 and on M1.

Finally, in the Eastern Pyrenees, a similar trend was observed each year, with a regular decrease in the number of ducks from F1 until A1. However, in 2009, the decrease in the number of birds seems to be observed since J3.

Bioacoustics

The main species identified by their call were mallards (*Anas platyrhynchos*), common shelducks (*Tadorna tadorna*), teals (*Anas crecca*), gadwalls (*Anas strepera*), wigeons (*Anas penelope*), garganeys (*Anas querquedula*), and shovellers (*Anas clypeata*).

However, most contacts were represented by bird movements (typical wing noise of ducks). Very few contacts, mallards and common shelducks removed, were recorded on Site 1 ($n = 35$) as compared to Site 2 ($n = 441$) (fig. 5). Two patterns were observed. In 2006 and 2008, we recorded an increase until F2, and then a decrease until A1. On the other hand, the opposite was observed in 2007 and 2009, with a decrease until F3, followed by an increase during the month of March. However, the statistical tests performed (χ^2 test and Bonferroni intervals) were not significant ($p > 0.05$).

RADAR

On Site 1 (fig. 6), according to the variable 'NESE', the earliest peak of low intensity (11.3 echoes/km/h) was detected during F1, in 2008 only, associated with prevailing flight directions towards NWNE. At no time did NESE flight direction seem to be the prevailing flight direction on F2, but it appeared to be so during F3, only in 2006. On the other hand, NESE flight direction seemed to be considerably favoured

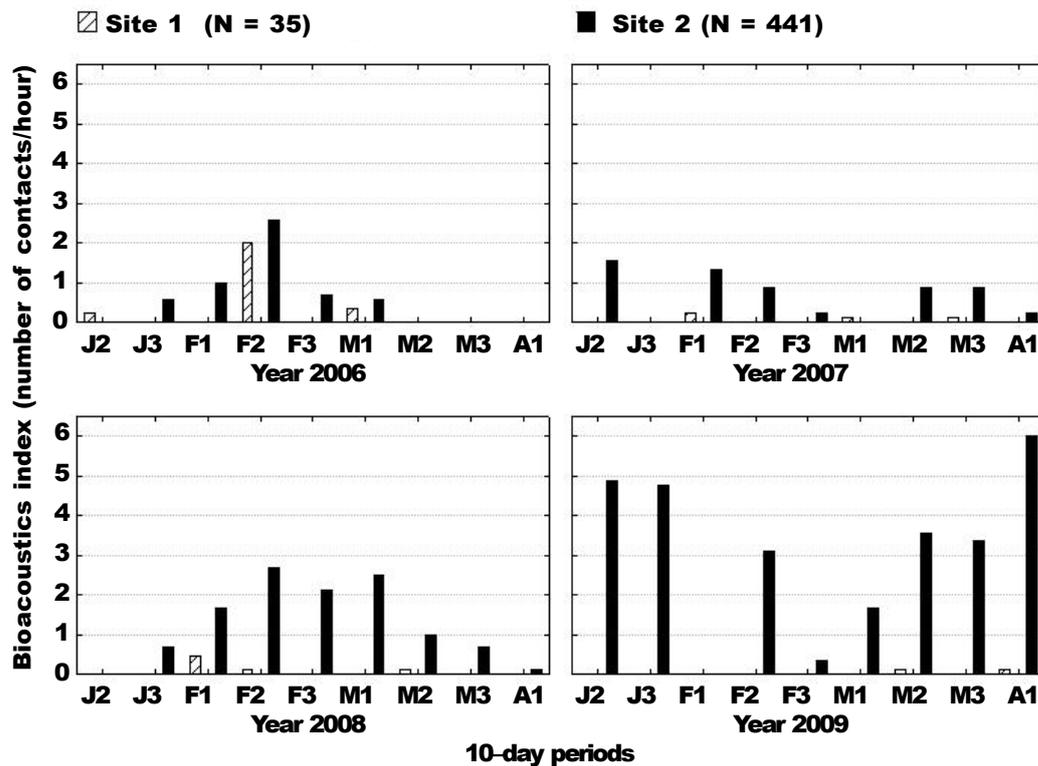


Fig. 5. Bioacoustics index (number of contacts/hour) of Anatidae without mallards and common shelducks according to 10-day periods for each year.

Fig. 5. Índice de bioacústica de Anatidae sin ánades azulones ni tarros blancos según los periodos de diez días para cada año.

during M1 and M3 throughout the four years of this study (MTR maximum of 57.3 echoes/km/h on M3 in 2008). Regarding the variable '> 400 m', very few echoes were recorded during J2 and J3 (maximum of 6.6 echoes/km/h on J2 in 2006). Then, a first peak of low intensity on F1 (2007) or F2 (2006) was observed. MTR values were always very low on F3 in the four study years. On the other hand, higher MTR values were recorded during M1 in 2006 and 2007, with a maximum of 406.4 echoes/km/h (2007) and during M2 (2006, 2008 and 2009). As for the variable '< 400 m', the MTR values were very low throughout the study period (maximum of 30 echoes/km/h on M2 in 2008).

On Site 2 (fig. 7), regarding the flight direction variables, a background noise was observed in January (which was not detected on Site 1). The variable 'NESE' seems to be privileged, firstly on F2 (2008), with a low MTR value (16 echoes/km/h). Then, this flight direction was considerably favoured on F3 but only in 2008. The most regular movements towards NESE seemed to occur during M2, with non-negligible MTR values in 2006, 2008 and 2009. Very few echoes were recorded, all flight directions combined, throughout the study period in 2007. According to the variable '> 400 m', the earliest peaks were recorded

on F2 in 2006 and 2007, and on F3 in 2007 and 2008. However, the MTR values of flight directions above 400 m were non-negligible on M2 (for the four study years), with the most important peak in 2008 (207.6 echoes/km/h). As for the variable '< 400 m', the MTR values seemed to be relatively low and seemed to increase from the month of March. However, these values were higher than those of Site 1.

In order to complete these observations, we performed a multivariate analysis (PCA). On Site 1 (fig. 8A), the two first axes (Fact.1 x Fact.2) of the PCA explained 84.75% of the variance ($\chi^2_{\text{obs}} = 38.31$, $p = 8.11 \times 10^{-4}$). Fact.1 is mainly represented by the flight directions towards North (NESE, 19.85% and NWNE, 14.61%) and by the flight altitudes (< 400 m, 22.75%, and > 400 m, 22.88%), that is to say, 80%. The direction towards SESW contributed for 19.85%. As for Fact.2, this axis was mainly represented by flight directions towards SWNW (74.6%) and towards SESW (12.68%), that is to say a total of 86.74%. This method separated two groups, opposed when we consider the Fact.1. The first group consists of 10-day periods in January and February and the second group of those in March, characterized by flight altitude variables and flight directions towards NESE and towards NWSE.

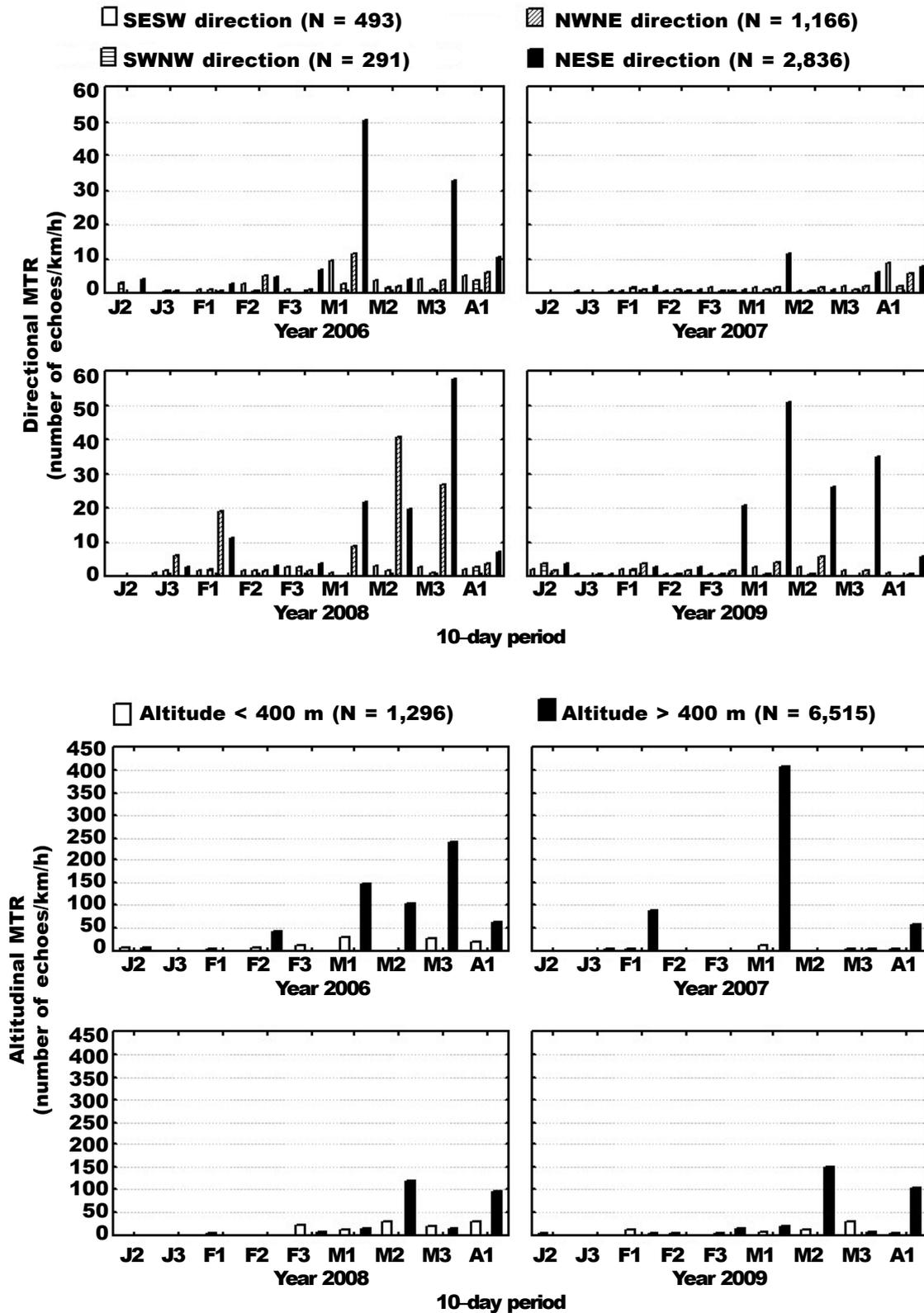


Fig. 6. Evolution of nocturnal MTR according to 10-day periods and years on Site 1.

Fig. 6. Evolución de las MTR nocturnas, según los periodos de diez días y los años en el Sitio 1.

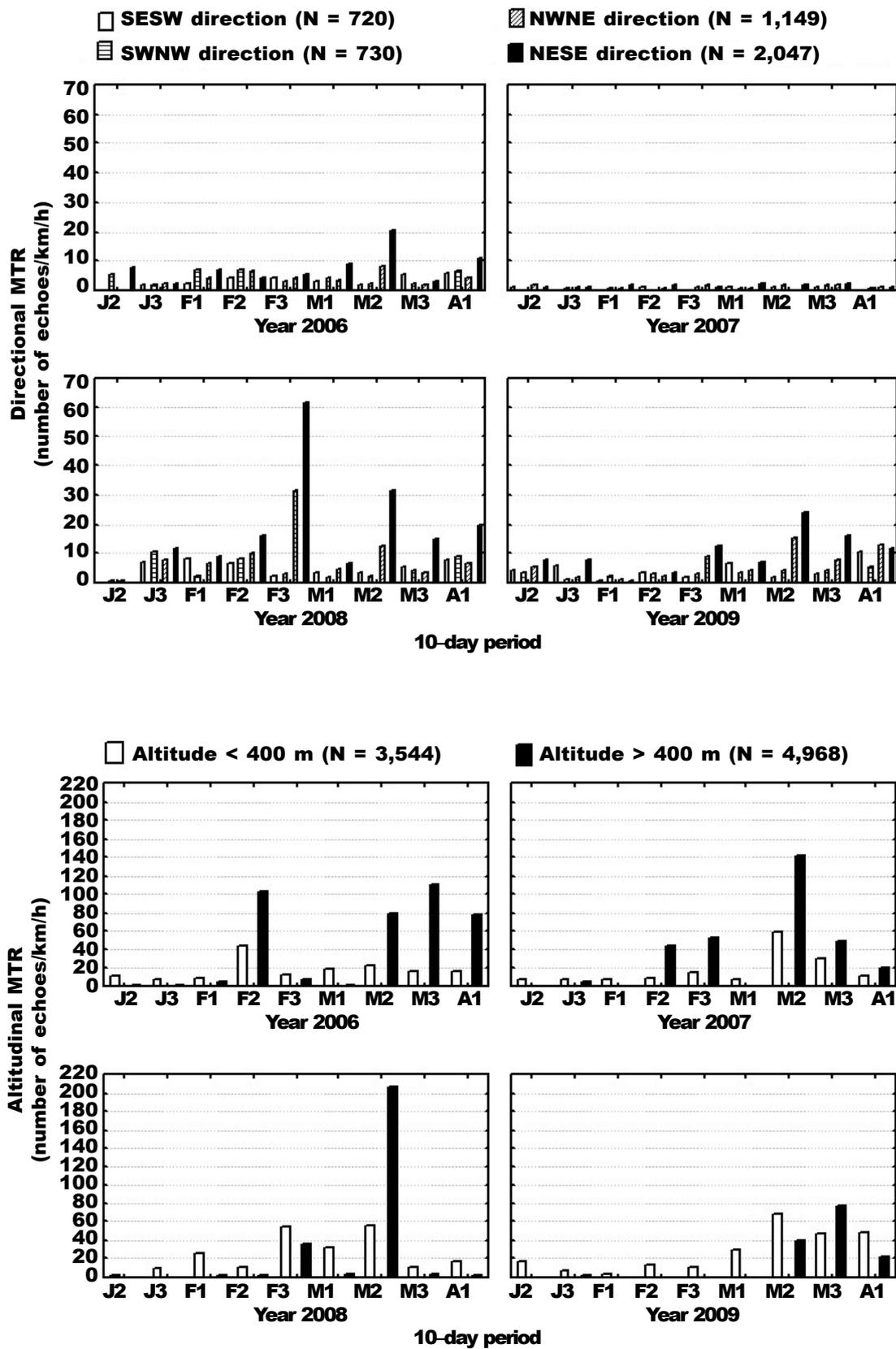


Fig. 7. Evolution of nocturnal MTR according to 10-day periods and years on Site 2.

Fig. 7. Evolución de las MTR nocturnas, según los periodos de diez días y los años en el Sitio 2.

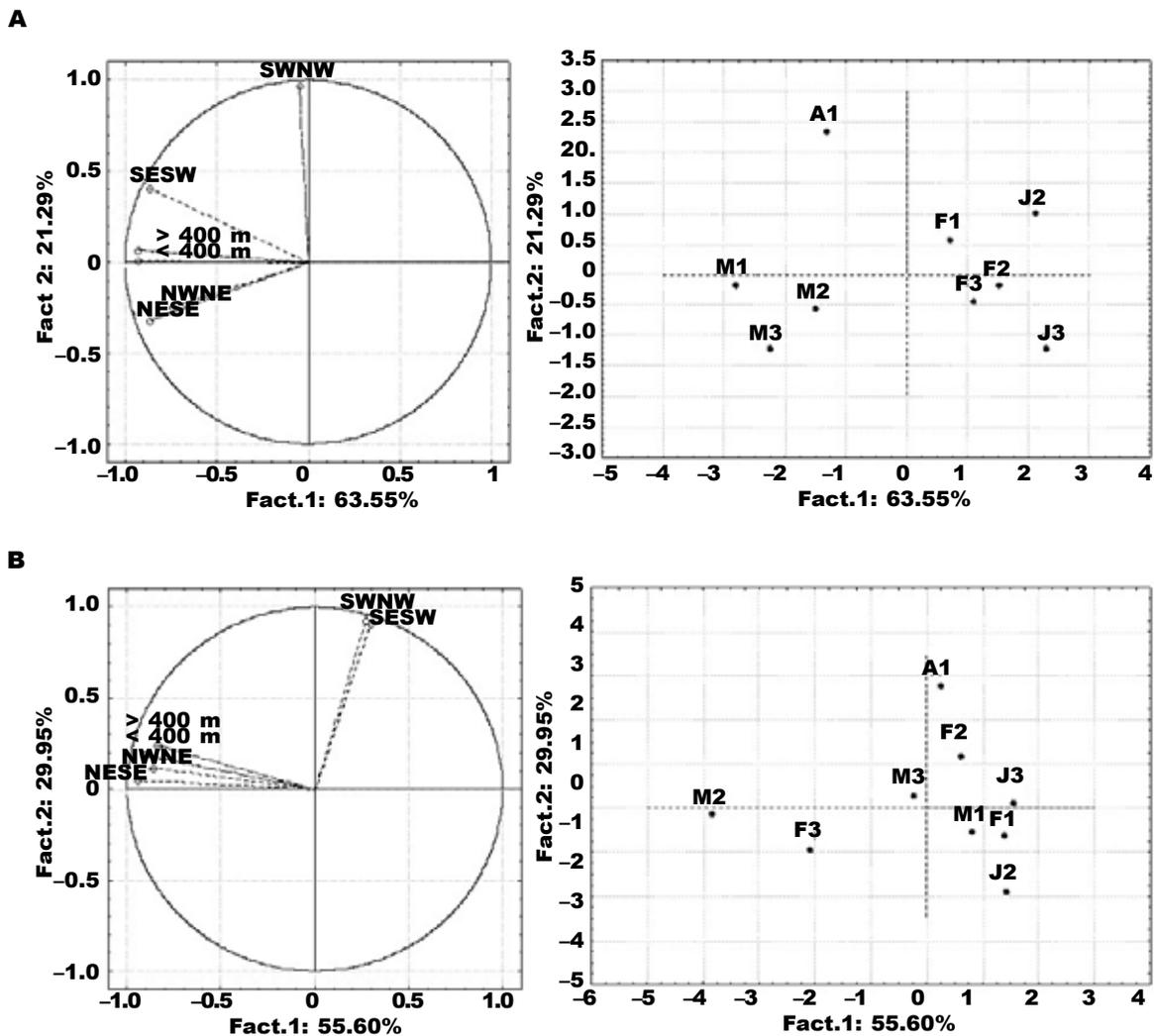


Fig. 8. Principal Component Analysis of average nocturnal MTR (2006 to 2009): A. Site 1, Feury d'Aude; B. Site 2, Camargue; J2, J3, F1, F2, F3, M1, M2, M3, A1. 10-day periods; NESE. Average nocturnal MTR towards North-East/South East; NWNE. Average nocturnal MTR towards North West/North East; SESW. Average nocturnal MTR towards South East/South West; SWNW. Average nocturnal MTR towards South West/North West; < 400 m. Average nocturnal MTR of flight altitude below 400 m; > 400 m. Average nocturnal MTR of flight altitude above 400 m.

Fig. 8. Análisis de Componentes Principales de los promedios de las MTR (tasas de tráfico migratorio) nocturnas (2006–2009): A. Sitio 1, Feury d'Aude; B. Sitio 2, Camargue; J2, J3, F1, F2, F3, M1, M2, M3, A1. Décadas; NESE. MTR nocturna media hacia el noreste/sureste; NWNE. MTR nocturna media hacia el noroeste/noreste; SESW. MTR nocturna media hacia el sureste/suroeste; SWNW. MTR nocturna media hacia el suroeste/noroeste; < 400 m. MTR nocturna media de las alturas de vuelo por debajo de 400 m; > 400 m. MTR nocturna media de las alturas de vuelo por encima de los 400 m.

On Site 2 (fig. 8B), the Fact.1 and Fact.2 axes of the PCA explained 85.5% of the variance ($\chi^2_{\text{obs}} = 45.59$, $p = 6.17 \times 10^{-5}$). Fact.1 was mainly represented by the flight directions towards north (NESE, 26.85% and NWNE, 22.30%) and by the flight altitudes (< 400 m, 24.82%, and > 400 m, 21.19%), that is to say, more than 95%. As for Fact.2, this axis is mainly repre-

sented by flight directions towards SWNW (47.73%) and towards SESW (46.20%), that is to say, a total of 93.93%. This method also separated two groups of 10-day periods (opposed on Fact.1) with one gathering F3 and M2, characterized by flight direction towards NESE and towards NWNE and flight altitude variables.

Discussion

Our results support that the use of two recently developed technologies (RADAR and bioacoustics recording) combined with a conventional method such as visual counts may improve the study of migratory bird movements. Visual counts provided an instantaneous number estimated throughout the study period. Thus, the analysis focused on bird number variations, but it is difficult to know what kind of movement may explain changes in numbers (migratory or local). This 'classical' approach seemed to identify two different patterns depending on the study areas. A regular decrease in duck numbers was observed on Site 2 and the Eastern Pyrenees since early February. According to MNHN & ONC (1989), this is considered typical of wintering sites and could be interpreted as wintering birds leaving their wintering areas. However, the interpretation of these trends is still difficult. A decrease in the number of birds from January to April can be interpreted as the result of local migratory birds leaving wintering areas, but it may also be the result of local movements due to several factors (disturbance, bad weather, food availability, etc.) (MNHN/ONC, 1989; Fouque et al., 1997; Guillemain et al., 2006). Moreover, decreases in numbers observed until late January at the study sites (fig. 4) could also be due to hunting, authorized until January 31st in France, a possibility we can not evaluate because hunting bags were unknown. The interpretation of increases in the number of birds observed during the study period is also difficult because this method does not give any information about flight directions or flight altitudes. Nevertheless, these observations may be interesting on Site 1, considered as a stopover area. In this case, an increase from mid-February through March (detected in three of four years) would better reflect migration, and could be interpreted as a consequence of stopover behaviour. Furthermore, we can not discard that data could be flawed by an observer effect, because depending on the years and the sites, observers may have changed. Finally, with only three censuses per month, the number of birds may remain stable if the number of incoming birds compensates for the number of departing birds (MNHN/ONC, 1989; Fouque et al., 1997).

Regarding bioacoustic results, this method seems to highlight F2 and F3 as turning point periods, because depending on the years, we observed the maximum (F2 in 2006 and 2008) or minimum (F3 in 2007 and 2009) values. However, it is difficult to reach sound conclusions because no tests performed were significant. Ricci et al. (1995) have worked successfully on thrushes, because these species emit many calls during their nocturnal migration flights. This is not the case with ducks. The analysis was therefore mainly based on the wing noise characteristic of ducks, minimizing the number of contacts. Moreover, such as with the first method, bioacoustic recordings can not detect the flight directions. Thus, the bioacoustics method does not seem to be appropriate to study this kind of species.

As we have seen, different biases may be linked to all methods. Overall, RADAR tracking seems to be the

most suitable method to study migratory duck movements at a population level. This tool is particularly interesting to study nocturnal movements (Bruderer, 2003) because it can detect targets to over 3 km, and it overcomes weather conditions (except for extreme events). We also know the flight directions and the flight altitudes, two variables needed to study migratory bird movements (at the strict sense). However, the RADAR used did not allow a wing beat analysis. The main current limitation is therefore the difficulty to identify echoes of birds at the species level (Hamer Environnemental, 2008; Schmaljohann et al., 2008). However, RADAR parameters were settled to avoid the detection of small-sized targets. Moreover, working within a range of 3 km (horizontally) and 1.5 km (vertically), and according to Alerstam (1976), we can assume that the echoes recorded exclude insects and small-sized migrants, such as small passerines (warblers, flycatchers, etc.). Furthermore, according to Arzel et al. (2006), Anatidae species are early migrants compared to other birds. The first migration peaks observed may therefore correspond to these species. The study sites were chosen for their location on the Mediterranean axis of the spring migration. Site 1 is particularly interesting because the wintering birds (Anatidae species) are fewer than on Site 2. This difference involves a limited 'background noise', contrary to Site 2 (fig. 7), due to an important number of local wintering birds. In future, in order to complete this study, it would be interesting to work on a site located at the north of Site 2 (Rhône valley, for example), to study the bird movements leaving the Camargue wintering area. The absence of background noise (wintering) would facilitate the interpretation of data, as was done by Ricci et al. (1995) regarding the chronology of the pre-nuptial migration of thrushes, with the simultaneous use of bioacoustic monitoring stations in areas with no wintering. However, in this case, it would remain difficult to distinguish birds leaving the Camargue (local departure of wintering birds) from those who fly over without stopping.

This study is based on two variables we considered as characteristics of migration: 'NESE' and '> 400 m'. Considering the MTR (figs. 6, 7), very low values were obtained for the variable '< 400 m' throughout the study on Site 1. On the other hand, the MTR values of the variable '< 400 m' recorded on Site 2 were slightly higher, particularly from F3 and during the month of March. We can not exclude that these echoes may correspond to migrant birds decreasing their flight altitude in preparation for stopover, or birds leaving their wintering area. However, from J2 to F2, these flows < 400 m were not associated with a prevailing flight direction. Although the distinction between migratory movements and more local movements can be arbitrary, and despite the fact that migratory movements with flight altitude < 400 m are possible, the results obtained, and particularly on Site 1 with a limited wintering population, would support that flight altitudes > 400 m, associated to flight directions towards north-east/south-east, could be used to study pre-nuptial migration. According to the PCA (figs. 8A, 8B), the 10-day periods of January do not seem to be

explained by the characteristic variables used (Fact.1). It appears there were no migratory movements during this period. Although two small increases were observed with the directional and the altitudinal MTR on F1 and F2 (figs. 6, 7), the PCA include these 10-day periods with those of January, indicating that these two 10-day periods are not linked as a migratory period. Moreover, the first peak detected during F1 on the Site 1 (fig. 6) is due to the winter 2007, particularly clement. Indeed, January and February 2007 were among the hottest months for the period 1950–2007, with a temperature of more than 3 degrees Celsius higher than the average temperature (Réseau OEZH, 2008). A peak was detected on F2 in 2006 (once every four years), but only for the variable '> 400 m'. Guillemain et al. (2006) have shown, by ringing, that teal (*Anas crecca*) spring migration in the Camargue (Site 2) starts during F1. Our results would not be in accordance with this conclusion, because the earliest movements (of low intensity) were detected during F2 in the same area (Camargue, Site 2). As Guillemain et al. (2006) suggest in their paper (data are from 1952 to 1978), migration dates may have changed due to the climate change or the modification of duck habitats. Therefore, these flows recorded during F2 could correspond to birds moving over short distances (possibility of leaving their wintering area), erratically, towards other feeding sites in order to obtain sufficient energy (as fats) to prepare their migration (Fouque et al., 1997; Newton, 2008). It may also be due to the phenomenon of nomadism (Newton, 2008; Boere & Dodman, 2010). Only an intensive monitoring on a large number of birds by Argos transmitters would allow these hypotheses to be tested. The MTR values and the PCA analysis, particularly at Site 2, seem to show that the first migratory movements occur during F3. We may assume that this 10-day period is a turning point in the pre-nuptial migration, separating two periods of different flow intensities. Indeed, the migration peaks with high values for the two migratory variables were detected in March (M1 on the Site 1 [fig. 6], and M2 on the Site 2 [fig. 7]). These results are consistent with those obtained by RADAR at a national level (LPO/Biotopie, 2008), estimating the period of pre-nuptial migration (all bird species combined) between March and mid-May. During M1 and M2, the RADAR echoes correspond to a wide diversity of nocturnal migratory bird species, including the Anatidae species, which are early migrants compared to many other birds (Arzel et al., 2006).

Although visual counts show a first decline in the number of birds from late January/early February, RADAR does not detect significant migratory movements before F3. Contrary to Guillemain et al. (2006), this study does not allow us to assert that diurnal censuses are a reliable method to study migration, particularly the complex pre-nuptial migration that is well defined in ORNIS (2008). This may be particularly true in an area like southern France, where sedentary and wintering populations may mix with migrant ducks coming from more southern locations. However, this study has shown that results provided by visual counts at the site considered as stopover (Site 1) were more similar to

RADAR results than those of an important wintering site (Site 2). Therefore, in order to study pre-nuptial migration in the future, we suggest that visual counts may be a feasible technique, but only at sites that are important as a stopover. We could have focused on one site but it seemed more appropriate to work on two remote sites to obtain more consistent results across the Mediterranean area. This paper has also demonstrated the need for RADAR use as the only way to study flight altitude and flight direction of nocturnal migratory birds at the population level. Although this tool is less precise for tracking only one species (unlike Argos transmitters or ringing), it is the most reliable for multi-species data, particularly for nocturnal migrants. In order to increase tracking efficiency, it would be interesting to use several Radars simultaneously on various sites with no wintering, but the cost in equipment and staff would be considerable. However, in this study, the results obtained provide scientifically relevant data about the phenology of pre-nuptial migration of duck species sharing a common area like wetlands, which is consistent with the principle of conservation biology.

To conclude, this article shows that the most significant period of pre-nuptial migration in the studied areas started during the first 10-day period of March. In most years we also found evidence of less important migratory movements during the third decade of February, probably reflecting inter-annual and inter-species variability. Finally, this study shows that there is no high-altitude NESE-directed migration up to F2, except for an atypically mild winter like 2007 (which was one of the hottest since the 1950s), when migratory movements could also be assumed in F1. To confirm these hypotheses, more research is needed and it will be interesting, in the future to performing RADAR monitoring at the north of Camargue, on a site with no wintering, to track ducks leaving this wintering area.

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