

Additional file 1: Supplementary details on methods

Data collection

Adults were captured using the following techniques: mist net with stuffed or live predator as lure, nest trap, catching pole or whoosh-net with carrion as bait. Nestlings were captured on the nest before fledging. Bird captures and tag deployment were performed with all necessary permissions. See Fig. S1 for the location of the study areas.

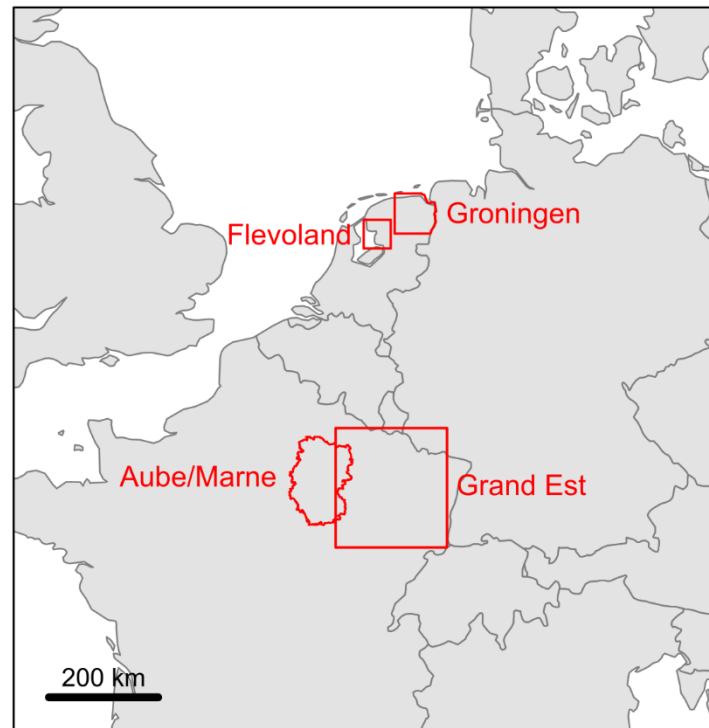


Figure S1: Location of the four study areas, and the boundaries applied. Background map created using the *R* package *maps* (1).

Some of the tag models were used in different versions in our study (with or without elevated solar panel [*Ornitela*], with different GSM network connectivity [*Ornitela*], with or without external antenna for communication with antenna system [*UvA-BiTS*]; Table S1), but these were lumped for the analyses as we did not expect differences in the vertical accuracy between tag model versions.

General data processing

The data were constrained to the four study areas, partly defined by rectangular bounding boxes and partly by administrative borders (Fig. S1). The latter were used where topographic data for the habitat classification were available for administrative units. 1st December 2022 was applied as the common end datum for the different data sets. However, barometric height data could only be used until the end of September 2022 because the ERA5 weather data (see Height data processing) were only available until then. The basic data processing was performed in the program *R* version 4.0.3 (2), using the packages *dplyr* (3), *sp* (4), *sf* (5) and *raster* (6).

As *Milsar* tags deployed in 2019 recorded erroneous height data during high-frequency sampling due to a firmware issue, high-frequency data from these tags were removed ($n = 56,300$). In two OT-25 tags deployed on Red Kites the pressure sensor failed permanently at a given moment in time; moreover, in two OT-15 and four OT-20 tags, in several instances the pressure measurements remained temporarily static during high-frequency blocks. The barometric height data for these positions were removed ($n = 382,436$ and $7,555$ for the two cases, respectively).

To determine the antimode in the distribution of GPS speed values for distinguishing between stationary and flight positions function *locmodes* from the *R* package *multimode* (7) was used (8). To allow determination of the antimode, the highest 0.1% of speed values were removed, although these data points remained within the general data set.

Subsampling was performed using a self-written function in *R*. As a minimum interval between positions, 5 min was used. Because GPS intervals are somewhat irregular (the actual interval can sometimes be smaller than 5 min when 5 min is the set interval in the tag settings), we included a tolerance of 30 s.

Table S1: Overview of GPS tracking data sets used in this study. The number of GPS and barometric height measurements per tag model include stationary and flight positions. Ind. = individuals; LF = low-frequency sampling; HF = high-frequency sampling, baro = barometric.

Manufacturer	Model	Model versions	Species	Area	Period	n tags	n ind.	n GPS LF	n GPS HF	n baro LF	n baro HF
UvA-BiTS	4C.L	4CWL	Marsh Harrier	Groningen	2012-16	2	2	704,150	645,431	0	0
UvA-BiTS	4C.L	4CWL	Montagu's Harrier	Groningen	2012-14	5	5	264,091	525,395	0	0
UvA-BiTS	4C.S	4CWS	Hen Harrier	Groningen	2012-15	3	3	122,734	360,594	0	0
UvA-BiTS	4C.S	4CWS	Montagu's Harrier	Groningen	2009-14	24	24	4,715	15,614	0	0
UvA-BiTS	5C.L	5CDL, 5CWL	Hen Harrier	Groningen	2014-15	1	1	60,778	173,344	0	0
UvA-BiTS	5C.L	5CDL, 5CWL	Montagu's Harrier	Groningen	2014-17	5	5	147,056	428,558	146,360	421,740
UvA-BiTS	5C.S	5CDS, 5CWS	Montagu's Harrier	Groningen	2015-20	10	9	125,994	272,912	125,994	270,099
UvA-BiTS	6C.L	6CDL, 6CWL	Marsh Harrier	Groningen	2014-21	3	3	587,953	2,647,694	467,952	2,178,229
Milsar	GsmTag-U9	GsmTag-U9	Hen Harrier	Champagne	2019-22	74	84	68,878	76,938	0	0
Milsar	GsmTag-U9	GsmTag-U9	Montagu's Harrier	Champagne	2020-22	11	11	35,108	60,776	0	0
Omitela	OT-10	OT-10-3GC, OT-10-3GC-C19, OT-E10-3GC, OT-E10-3GC-C19, OT-E10-4GC	Hen Harrier	Champagne	2021-22	15	16	89,724	81,045	0	0
Omitela	OT-10	OT-10-3GC-C19	Montagu's Harrier	Champagne	2021-21	2	2	349,356	1219,773	0	0
Omitela	OT-10	OT-10-3GC	Montagu's Harrier	Groningen	2021-22	3	5	21,499	0	0	0
Omitela	OT-15	OT-15B-3GC-C21	Marsh Harrier	Flevoland	2019-22	4	5	33,010	172,075	0	0
Omitela	OT-20	OT-20B-3GC-C21	Marsh Harrier	Flevoland	2019-22	7	7	103,654	304,556	0	0
Omitela	OT-25	OT-E25B-4GC	Red Kite	Grand Est	2021-22	26	28	163,069	911,170	0	0
Total					2009-22	194	204	2,881,769	7,895,875	740,306	2,870,068

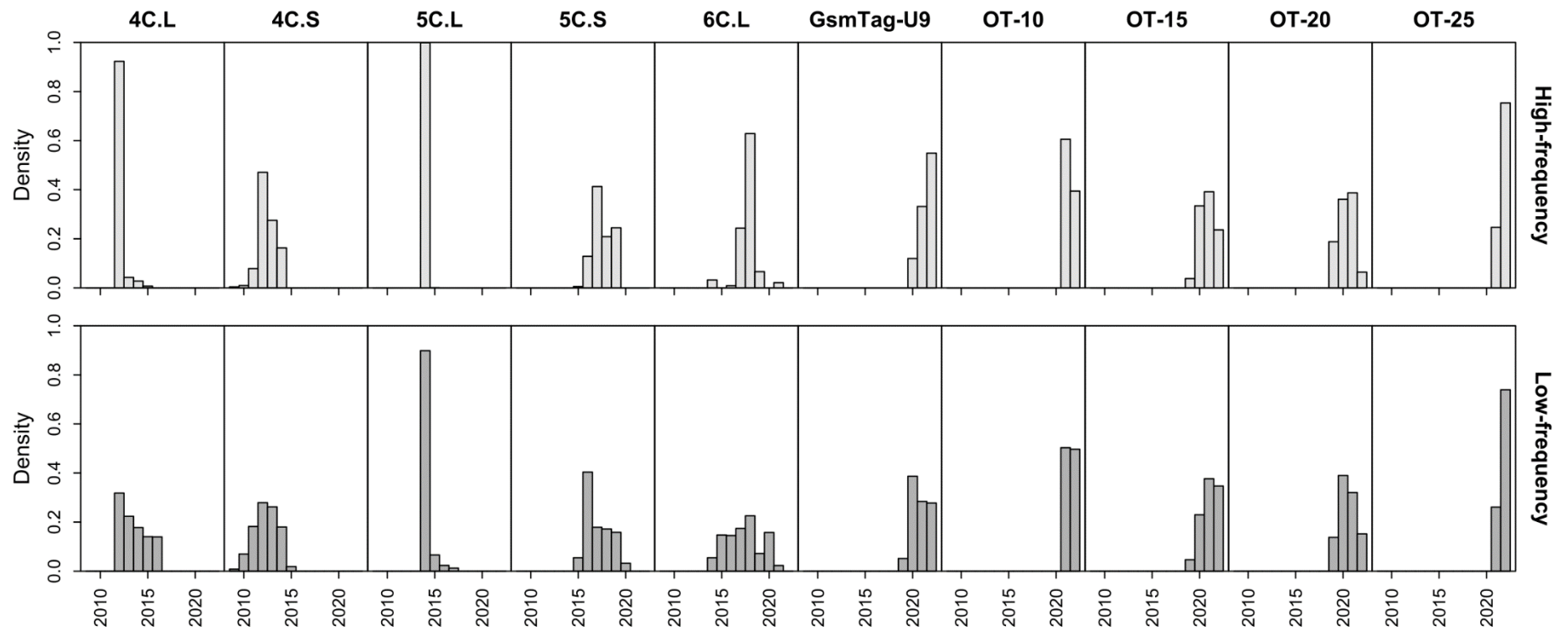


Figure S2: Distribution of the high- and low-frequency tracking data across years per GPS tag model. Histogram bins represent years between 2009 and 2022.

Height data processing

The calculation of barometric height based on the pressure measurements of the tags was performed using the barometric formula describing the relationship of air pressure with height above a reference level under different meteorological conditions $P = P_0 * (1 + \frac{L}{T_0} * z)^{-\frac{g}{LR_0}}$ (9; Equation 1), where P is the measured pressure at height z above the reference height level, P_0 is the pressure at reference height, L is the temperature lapse rate, T_0 is the temperature at reference height, g is the standard acceleration of free fall (9.81 m s^{-1}), and R_0 is the specific gas constant ($287.05 \text{ J K}^{-1} \text{ kg}^{-1}$). The data provided by the tags had already internally been transformed into height above sea level (a.s.l.) using the inversion of Equation 1, but using the values of the standard atmosphere $P_0 = 1013.15 \text{ hPa}$, $L = -0.0065 \text{ K m}^{-1}$, and $T_0 = 288.15 \text{ K}$. In some tags, the manufacturer erroneously applied $T_0 = 287.15 \text{ K}$ (R. Zydelis, pers. comm.). To improve the height estimation by integrating actual weather data in the formula, we first transformed the height a.s.l. obtained from the tags into the original pressure measurements using Equation 1. Secondly, we applied the inversion of Equation 1 to calculate height using weather data from the global weather model ECMWF ERA5 with a temporal resolution of 1 h and a spatial resolution of 15' (10,11). The tracking data were annotated with ERA5 data using the Environmental-Data Automated Track Annotation System (Env-Data) provided by Movebank (12), which included an interpolation of the ERA5 data to the timestamp and horizontal position of each GPS position. We used “Surface Air Pressure” and “Temperature (2 m above Ground)” provided by ERA5 as P_0 and T_0 , thereby using the surface level of ERA5 as reference level. To obtain an estimation of L , we calculated the temperature gradient between the model surface and a higher pressure level for which the temperature could be retrieved from ERA5 (950 hPa for Red Kite data from Grand Est, 975 hPa for Marsh Harrier data from Flevoland). The geometric height a.s.l. of both the model surface and the pressure level were calculated based on the geopotential ϕ provided by ERA5 for these levels, using the equations $H = \frac{\phi}{g}$ (Equation 2) and $h = \frac{r * H}{r - H}$ (Equation 3) where H is the geopotential height, ϕ is the geopotential, h is geometric height a.s.l. and r is the nominal earth's radius, i.e. 6,356,766 m (9). (Note that there is barely any difference between geometric and geopotential height at the altitude ranges considered here.) The pressure levels were on average 286.4 m (Grand Est) and 355.7 m (Flevoland) above the ERA5 surface level. Note that due to the spatial resolution of the ERA5 model of 15', the ERA5 surface is a coarse approximation of the earth's surface. Therefore, we did not use the height of the tracking data above the ERA5 surface directly as height above ground level (a.g.l.), but first calculated height a.s.l. by adding the height of the model surface a.s.l., and then applied a digital elevation model with higher spatial resolution.

The geoid model used in ERA5 was EGM96, as for the GPS tracking data. However, the EU-DEM digital elevation model was based on another geoid model (EEG2008). Therefore, we assessed the difference between EGM96 and EEG2008 by comparing the geoid height above ellipsoid from both geoid models across all positions of our GPS tracking dataset. EGM96 raster data with spatial resolution of 15' were downloaded through (13); EEG2008 raster data with resolution of 10' x 15' through (14). As

the difference between the two geoid models was small (mean absolute difference 0.12 m, maximum 0.65 m), we refrained from applying further corrections of the data.

Identification of stationary positions on the ground

For the three species of harriers which are known to sit on the ground most of the time when being stationary, we used the digital national topographic maps *BD TOPO* for France (15) and *TOP10NL* for the Netherlands (16). We applied the topographic data from the mean year of the available tracking data per study area (pooled across species), i.e. 2021 for Champagne, 2021 for Flevoland and 2015 for Groningen, with the exception of the *BD TOPO* hedgerow layer for Champagne which was only available for 2022. The spatial overlay was performed using functions from the *R* package *sf* (5).

Visual checks of the classification results with satellite images on a sample basis indicated only few instances of misclassification, all referring to positions erroneously classified as “non-ground positions” (parcels of land where forest had been converted to agricultural land, which was not yet updated in the topographic data). This does not have major implications for our results, as we base our analysis on “ground positions” only.

Table S2: Overview of layers and object types used from the national topographic maps *BD TOPO* (France) and *TOP10NL* (Netherlands). English translations of the names of layers and object types are indicated in brackets. To all the listed objects a buffer of 50 m was applied to identify GPS positions on or close to vertical structures (see Methods).

Data set	Layer	Object type	Geometry type
BD TOPO	“zone_de_vegetation” (vegetation zone)	All	Polygon
BD TOPO	“batiment” (building)	All	Polygon
BD TOPO	“haie” (hedgerow)	All	Line
BD TOPO	“pylone” (pylon)	All	Point
TOP10NL	“Inrichtingselement” (structural element)	All	Line/point
TOP10NL	“Gebouw” (building)	All	Polygon/point
TOP10NL	“Terrein” (terrain)	“bebouwd gebied” (built-up area), “boomgaard” (orchard), “boomkwekerij” (tree nursery), “bos: gemengd bos” (mixed forest), “bos: griend” (osier bed), “bos: loofbos” (deciduous forest), “bos: naaldbos” (conifer forest), “dodenakker met bos” (cemetery with forest), “fruitkwekerij” (fruit orchard), “populieren” (poplar trees)	Polygon

For Red Kites, we classified the perching habitat manually by visual inspection of satellite pictures. This procedure was applied to a subset of the data (data from 2021). The visual inspection was performed using satellite images accessed using the *R* packages *OpenStreetMap* (17) and *plotKML* (18), and the program *Google Earth*.

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