Physical and Migration Metrics of White Storks (*Ciconia ciconia*) and the influence that landfills play in their variation

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Summary

1. White storks (*Ciconia Ciconia*) are a traditionally fully migratory species and their numbers in western Europe were decimated in the last century. Their numbers have since boomed and they have altered their migratory strategy to have become a partially migratory species. This change has been ascribed in large part to anthropogenic food subsidies, particularly in the form of landfill sites.
2. We measured the size, and using GPS logger data monitored the movement, of 73 juvenile white storks in their first migration from southern Portugal to the Sahel. We compared their sizes and migration timings and movement metrics with each other and compared all with the minimum distance between their nest and a landfill site.
3. Birds were larger and left their nests later the closer to a landfill they were raised. Some variations in migration were noted in north Africa and crossing the Sahara. Birds raised closer to landfills traversed from Tangiers south across the Atlas Mountains more efficiently, but then crossed the Sahara more slowly, than those raised farther from landfills. Additionally, based on landfill distance, variations in easting whilst crossing the Sahara were noted.
4. We conclude that landfill proximity impacts on the fitness of a bird and that fitter birds successfully complete more migrations. The impact of removal of landfill food subsidies could severely impact the annually resident population of white storks within western Europe but is unlikely to cause serious issues to the migrant populations.

Introduction

There are almost 10,000 recognised bird species globally, and nearly 20% of these undertake an annual migration, mostly within the northern hemisphere (Somveille, Rodrigues, & Manica, 2015). As of 2008, 11% of migratory bird species were classed by the IUCN as Threatened or Near Threatened (Kirby et al., 2008), making it important to understand the underlying causes of any recent population declines. Migrations range from intra-regional to inter-continental, and have different movement strategies, from vast non-stop journeys to staccato trips with many short legs and frequent refuelling stops. There is an ongoing pattern of population decline amongst Palearctic-African migrants, with much of the cause being ascribed to changing land use and intensification of agriculture in both the breeding and non-breeding landscape (Kirby et al., 2008). Birds breed in areas that can provide safety and abundant resources, but once the seasons begin to change, migration occurs as birds then leave to increase their survival chances, by avoiding harsh winter conditions and reduced resources (Newton, 2008; Somveille et al., 2015).

Mankind, for many reasons and in many ways, provides reliable and readily accessible food resources to wildlife, with what have become known as Predictable Anthropogenic Food Subsidies (PAFS). In some guise, these have been an ongoing source of nutrition to animals for millennia (Oro, Genovart, Tavecchia, Fowler, & Martínez-Abraín, 2013). Subsidies occur in a variety of forms and sources. Some are intentional ranging from hanging bird feeders in one's garden, through to large conservation programmes assisting in the maintenance and recovery of endangered species (Tauler-Ametller, Hernández-Matías, Pretus, & Real, 2017). PAFS are frequently supplied unintentionally too, and landfills are a major component in this category. They impact on the ecosystems in which they are sited and can influence the density and number of species and individuals within their area (Olea & Baglione, 2007). Landfill resources have been shown to increase and improve individual condition, breeding success and survival in many species (Plaza & Lambertucci, 2017), but not all impacts are positive, with consumption of harmful plastics and pathogens also being recorded (Henry, Wey, & Balança, 2011) and (Monaghan, Shedden, Ensor, Fricker, & Girdwood, 2017). The increase in food resources from landfills, particularly when in conjunction with global climate change, could have an impact on the need for certain species to migrate.

White storks (*Ciconia ciconia*) are Palearctic migrants that are traditionally wholly migratory from Europe during the autumn season (Rotics et al., 2016). They have breeding sites from north Africa, through Europe and into western Asia, with different regional populations having various migration routes and timings (Flack et al., 2016). White storks soar on thermals to migrate vast distances, enabling them to avoid inhospitable environments and reducing their need for stopovers. Soaring species actively choose their migration routes and times to benefit from stronger thermals and reduce travel costs (Flack et al., 2016). Thermals are found over land and are greatly reduced over water, causing migration routes to rarely be direct, as detours become a necessity to cross large water bodies at their narrowest points (Kirby et al., 2008). The Mediterranean Sea is a large barrier to migratory birds (RSPB, n.d.), and the Strait of Gibraltar as the narrowest point at which birds from western Europe can cross, is used by many species, including white storks (Martín, Onrubia, de la Cruz, & Ferrer, 2016). These bottleneck points cause great densities of birds to occur, and it is at these points that they are most vulnerable to anthropogenic disturbance such as hunting or manmade structures (windfarms for example), (Kirby et al., 2008). The Sahara Desert poses a physically larger and tougher challenge, and in a study of migrating raptors, over 40% were seen to behave erratically during their attempted crossings, and 31% of juveniles died whilst crossing during their first migration (Strandberg, Klaassen, Hake, & Alerstam, 2010). Changes in the pattern and counts of migrants may be expected if population sizes change over large areas, and monitoring these could facilitate in detecting major population trends (Martín et al., 2016).

White storks are an ideal study species as they are plentiful, physically large and iconic. Their large size aids in long term monitoring projects as it allows for the attachment of large and easily identifiable rings, viewable without recapture, by expert and amateur alike. It also allows for the fitment of loggers that can gather and transmit a host of movement and location data. Their frequent study has provided us with detailed knowledge on their population dynamics, breeding, and migratory behaviour (Flack et al., 2016). White storks are long-lived and adapt well to the environmental changes they experience over their lives and as a species. In the 1970's the population in western Europe underwent a drastic decline, almost to the point of extinction in some areas (Massemin-Challet et al., 2006). This decline was mostly due to anthropogenic activity, and reintroduction programmes were implemented in some areas, using artificially bred and fed birds, (Massemin-Challet et al., 2006). Populations have subsequently grown such that they are classed as being of least concern (IUCN, 2016). Not only have migratory populations doubled over the past two decades but studies have indicated that the abundant, reliable and year-round food supply from landfills has enabled what were wholly migratory populations to become only partially migrant now. The non-migrant populations utilise landfills year-round and resident numbers have grown to seven times those of 20 years ago (Verde & Unido, 2005). Studies have also shown that during breeding season, all birds increase foraging activity, but that more time is spent foraging by those farther from landfills, and that those closer to landfills spent longer displaying resting behaviour (Gilbert et al., 2015).

There is an EU directive to drastically reduce the amount of food and organic waste that is disposed of on open landfills, ultimately to the point of complete removal (European Parliament and Council, 2008), and any alteration to a reliable food supply can seriously impact those that rely on it for their survival (Mateo-Tomás & Olea, 2010).

White storks are a species that have been affected by landfill resources and that have undergone population and migration changes, implying an apparent correlation between land use and proximity to landfills with stork survival and population numbers.

This study examines the migration aspect of juvenile white storks and their first journey from southern Portugal to the Sahel. It does so in conjunction with measuring and comparing morphological characteristics, by measuring an individual's size and comparing whether and how it migrates. It then models if and how the physical and migratory metrics vary as a function of the distance from natal nest to its closest landfill. The hypotheses are that landfills have a positive effect on the growth and condition of storks, and that the young will be larger, migrate later and more successfully the nearer to a landfill that they were raised. Understanding the role of habitat use and anthropogenic food sources on migratory as well as static populations will enable us to better manage conservation strategies in the future.

Materials, Methods and Data

Stork Tagging

This project is part of a long-term study started in 2013 examining the movement ecology of white storks that breed in southern Portugal. The main study centres around the area of Castro Verde (37.6996° N, 8.0866° W), with a secondary area further south centred near Portimao at (37.1847° N, 8.5458° W). Landfills within the region were identified and their GPS positions noted, and twelve stork colonies were selected so as to provide an equal number near and far from landfill sites (<15 km and >15km) (Rogerson unpubl.) (Figure 1).

73 juvenile white storks were fitted with GSM-GPS data loggers (Movetech Telemetry), in spring and summer of 2016 (n=41) and 2017 (n=32).

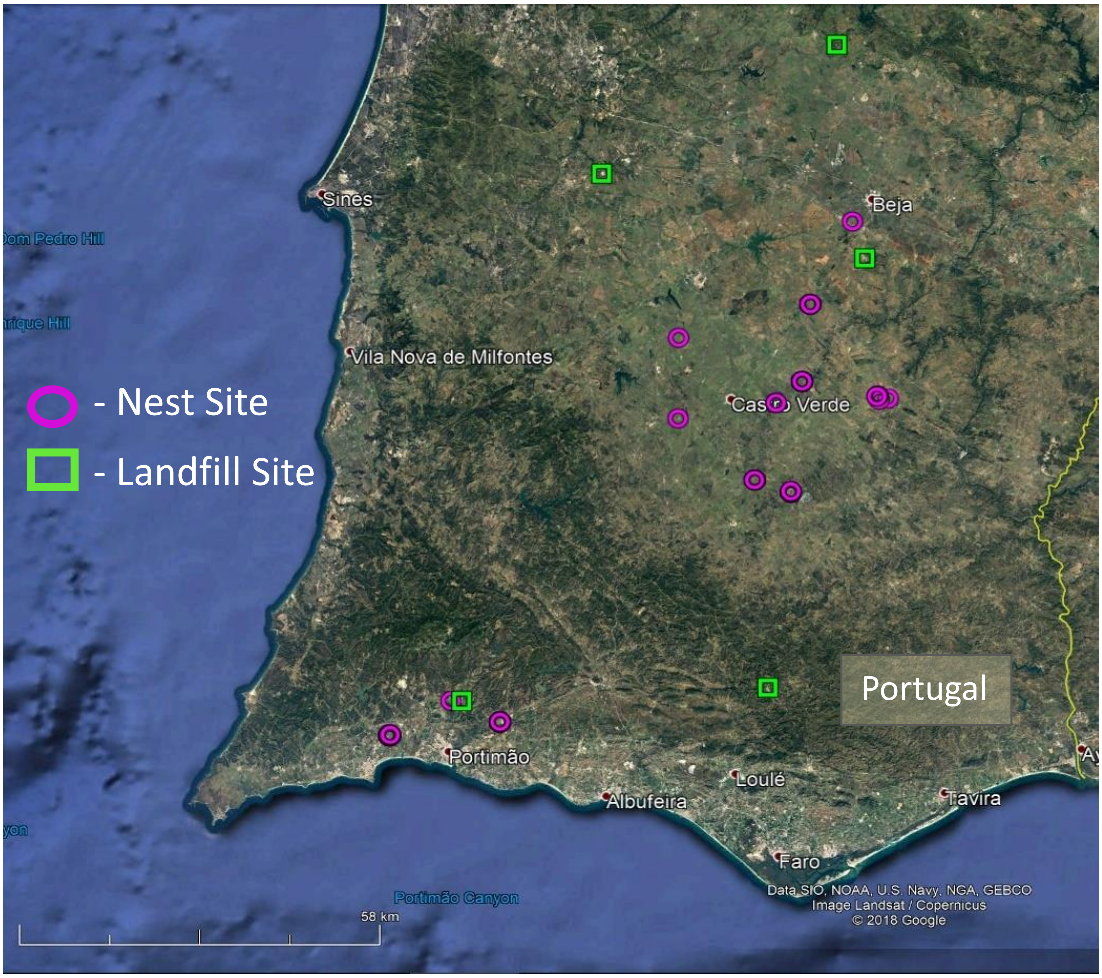
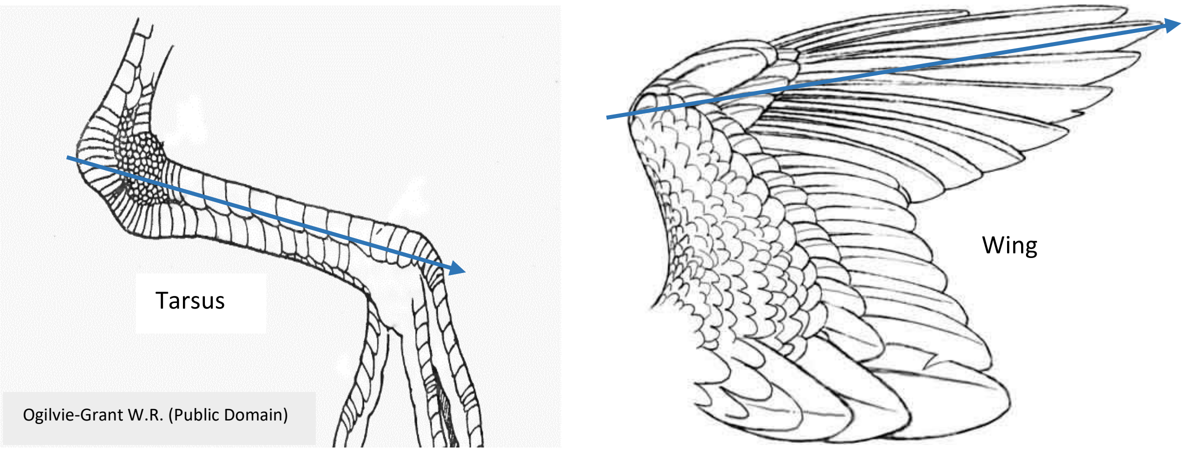


Figure 1. Area of study and location of nests and landfills used in this project.

Physical Readings, Logger Deployment and Datasets

Within the 12 colonies, specific nests were identified that were readily and safely accessible and contained large pre-fledge juveniles. The GPS location of each nest was recorded, and following procedures adopted in Gilbert et al., (2015), juveniles were fitted with a tracking device and their morphological parameters, including weight, external measurements of the folded wing from wrist to tip of the primaries, and of the tarsus (Figure 2) were collected. Loggers weighed 80g, equating to less than 3% of the weight of 69 of the 73 birds fitted, and less than 4% of the weight of the other four. The loggers took readings daily, starting at 01:00 and then at 20-minute intervals from 05:00 to 21:00. Data were stored onboard and transmitted via GSM and uploaded to Movebank (movebank.org, studies "White Stork Juveniles 2017" and "White Stork Adults and Juveniles 2016"). Two of the loggers lost data during a portion of their migration, and these were excluded from calculations in which the missing data should have been incorporated.



Ogilvie-Grant W.R. (Public Domain)

Figure 2. Measurements taken of juvenile white storks at the time of logger deployment included the external tarsus length and the wing length from wrist to the tip of the longest primary of the folded wing.

Migration Metrics

A bird was determined to have permanently left its nest when a displacement of more than 70km occurred. It was found by observation, and confirmed by logger data, that juveniles did not return to their nests once they had displaced by this distance. The date a bird left its nest was defined as that when the first reading of the day was more than 70km from its nest. Carrying this theme forward, migratory move and stopover days were also defined as those having a daily displacement of greater or less than 70km respectively. Beginning of migration required five consecutive move days, and the start date was the first of those five days. Migration end was decided by five consecutive non-move or stopover days, and the end date being the first of those five. The migratory route was divided into three legs based on physical geographic barriers (Figure 3), with each leg broken down further into days. Days and legs were defined by the 1st logged reading of one until the 1st logged reading of the next, these usually occurred between 01:00-01:20. The last day and last leg included and ended on the last reading of the predefined end of migration date.

Leg 1 started from the date and point where the first reading of the day was over 70km from the nest, and not from the official migration start date, which generally occurred either on or after the day of crossing the Strait of Gibraltar. This would not have allowed for the calculation of days and distances in Iberia once leaving the nest. The leg carries on until the bird crosses south of the 36° parallel, which is just off the southern tip of Gibraltar. At the end of the first leg, the Strait of Gibraltar forms the first physical barrier of their journey. As soaring migrants, white storks rely on thermals for long distance flight (Leshem & Yom-Tov, 1996), which are massively reduced over large areas of water such as the Strait of Gibraltar.

Leg 2 starts at the 36° parallel and heads south, over the Atlas and Anti-Atlas Mountains until the 30° parallel. The mountains themselves form a barrier, over, around or through which the birds must navigate. On the southern side of these mountains are farmlands and areas for birds to recoup and take up resources if required. The 30° parallel is taken as the entry to the Sahara, beyond which there were limited supplies and most birds did not stop until they passed the 20° parallel.

Leg 3 went from the 30° parallel south across the Sahara Desert and finished at the predefined date of migration end.

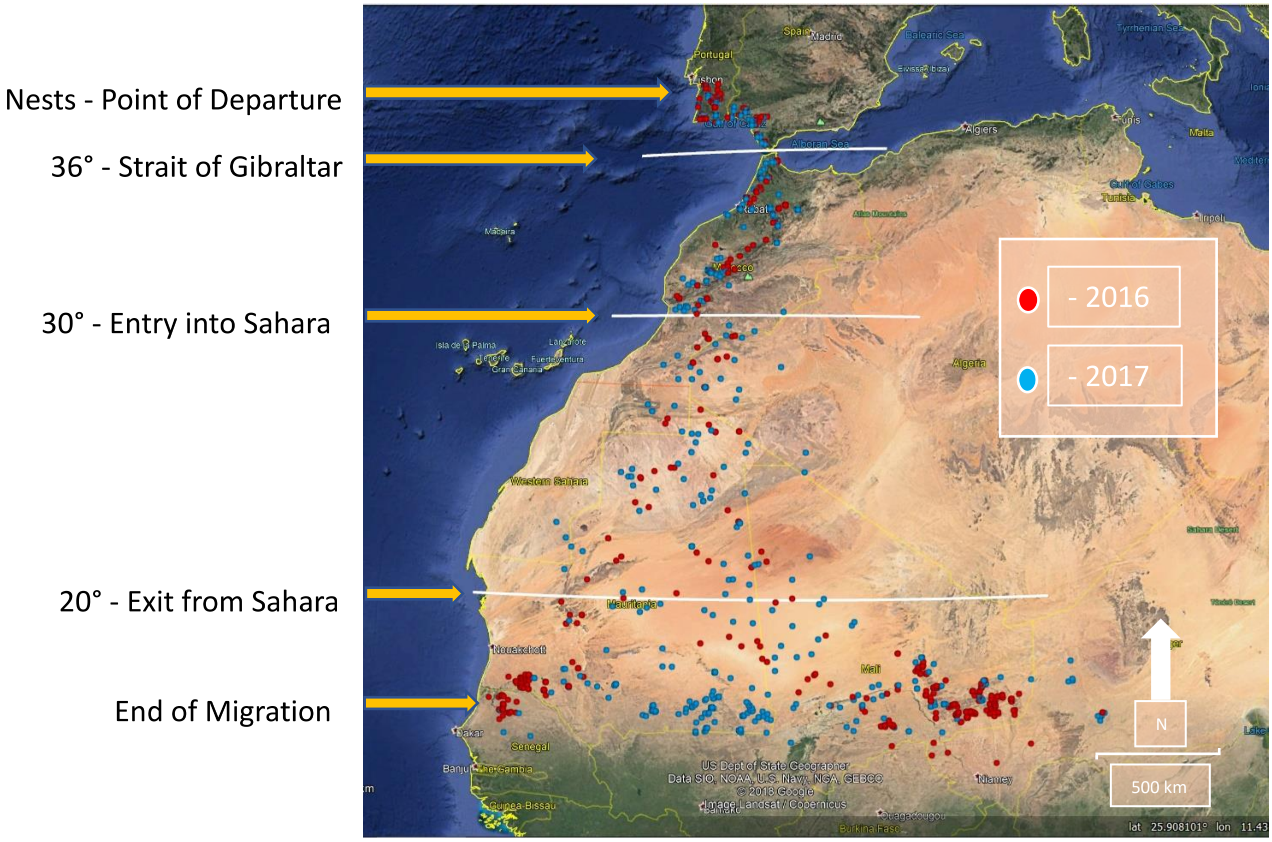


Figure 3. Migration routes of white storks in 2016 and 2017 from southern Portugal to the Sahel broken down into 1 point per bird per day. Boundaries of migration legs defined for use in analysis are shown. The 20° parallel is not a leg boundary but was used to define the edge of the Sahara.

Data Manipulation and Calculations

Distances between nests and nearest landfill sites were calculated from their respective GPS coordinates in MSOffice Excel using (gis.stackexchange, n.d.).

Altitude, speed and distance were determined as important migration metrics (Vansteelant, Kekkonen, & Byholm, 2017). Readings were filtered by ground speed, and only those with speeds greater than 1.39m/s (5kmh) were included, as speeds below this were classed as walking or localised movement and not as migratory flight (Rotics et al., 2016). No filtration was applied based on time of day, allowing for incorporation of all movement by day or night.

Dates – All logger dates were given as a timestamp with date and time. These were converted to individual Gregorian Date and Time columns, and then all dates were converted to Julian Date (as day of year, leap years considered), using the lubridate package in R (Grolemund & Wickham, 2011).

Altitude – was provided as that above an ellipsoid, which was converted to height above mean sea level (AMSL). The difference between Geoid Height and Ellipsoid Height per GPS point was calculated online using (EGM2008 Development Team, 2008). Each point's height AMSL was then calculated by subtracting the geoid-ellipsoid difference from the logged height above ellipsoid.

Distances – between logged migration points were calculated using geosphere R package (Hijmans, 2017).

Daily Metrics

Daily distance was calculated as the sum of the distances between every migration point within a day, from the first reading of the day until the first reading of the next day.

Daily displacement was calculated as the straight-line distance between the first reading of the day and the first reading of the next.

Daily efficiency was calculated by dividing the actual daily distance by the daily displacement.

Speed and Altitude per day were calculated as the mean of every reading on a given date.

Leg Metrics

The first night away from the nest was the first day of leg 1 and the migration end date was the last day of leg 3. Cross overs between legs 1-2 and 2-3 occurred during the day, and all readings on the day of crossover were allocated to the leg the bird was in at the start of that day. Measurement of the new leg only started from the first reading of the next day.

Leg displacement was calculated from the first reading of the day in the leg until the first reading of the day of the next leg (or the last reading of the last day in the case of leg 3).

Leg efficiency was calculated as the summed daily displacements for the leg, divided by the leg displacement (Figure 4).

Leg speed and altitude were calculated as the means of each daily mean within the leg.

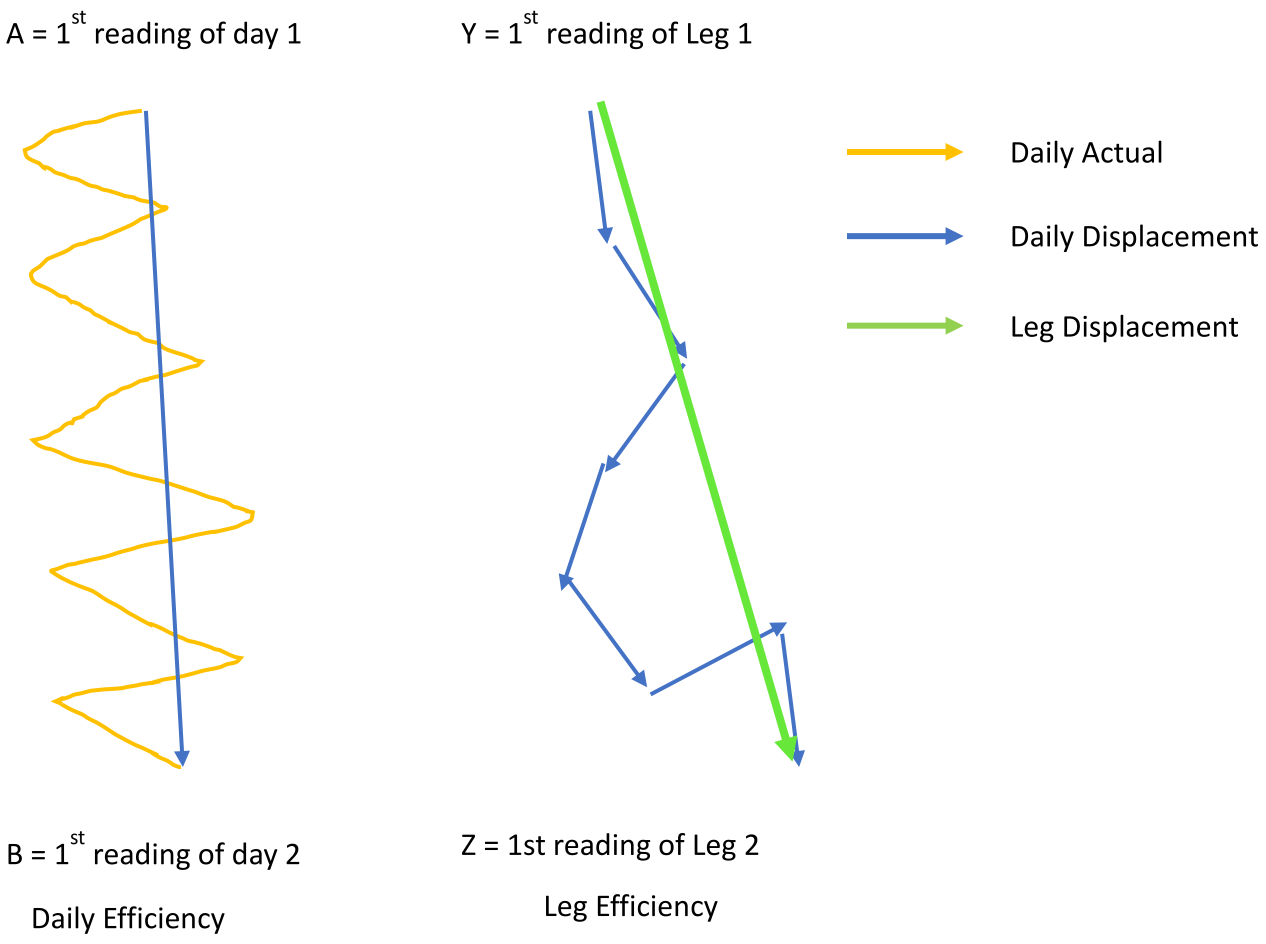


Figure 4. Visual representation of the migration efficiency metric. By dividing the actual daily distance travelled by daily displacement and the summed daily displacement by leg displacement, fractional efficiencies are derived.

Body Condition Indices

As a way of accounting for age and natural size variation, two Body Condition Indices (BCI's) were calculated. In preliminary data exploration, tarsus length showed a significant relationship with weight ($\beta=23.59$, $p<0.001$, $R^2=0.49$), (Figure 5), but wing length did not ($\beta=0.21$, $p=0.89$, $R^2=0.00$).

A Wing-Weight Index (WWI) was calculated by dividing weight by wing length. In addition, a Tarsus-Weight Index (TWI) was calculated for each bird, based on the weight~tarsus_length model, and was given as the residual value of actual weight to calculated weight. This provided a metric of weight above or below expected, based on tarsus size. These two indices have been referred to individually, or together, as Body Condition Indices (BCI's). Table 1 summarises the raw and calculated data that were used in the final analysis of this study.

Statistical Analysis

Mean BCI's, split by migration success were analysed using Welch's 2-sample t-tests (which assume non-normality of distribution). The main comparisons of migration and morphometrics against distance to landfill and BCI's were performed using linear regressions and used only one predictor variable with no interactions, all of which were performed using base R package (R Core Team, 2017).

Of the 73 birds fitted with loggers, 41 were in 2016 including 10 that logged complete outward migrations, and 32 were in 2017 of which 14 logged full migrations.

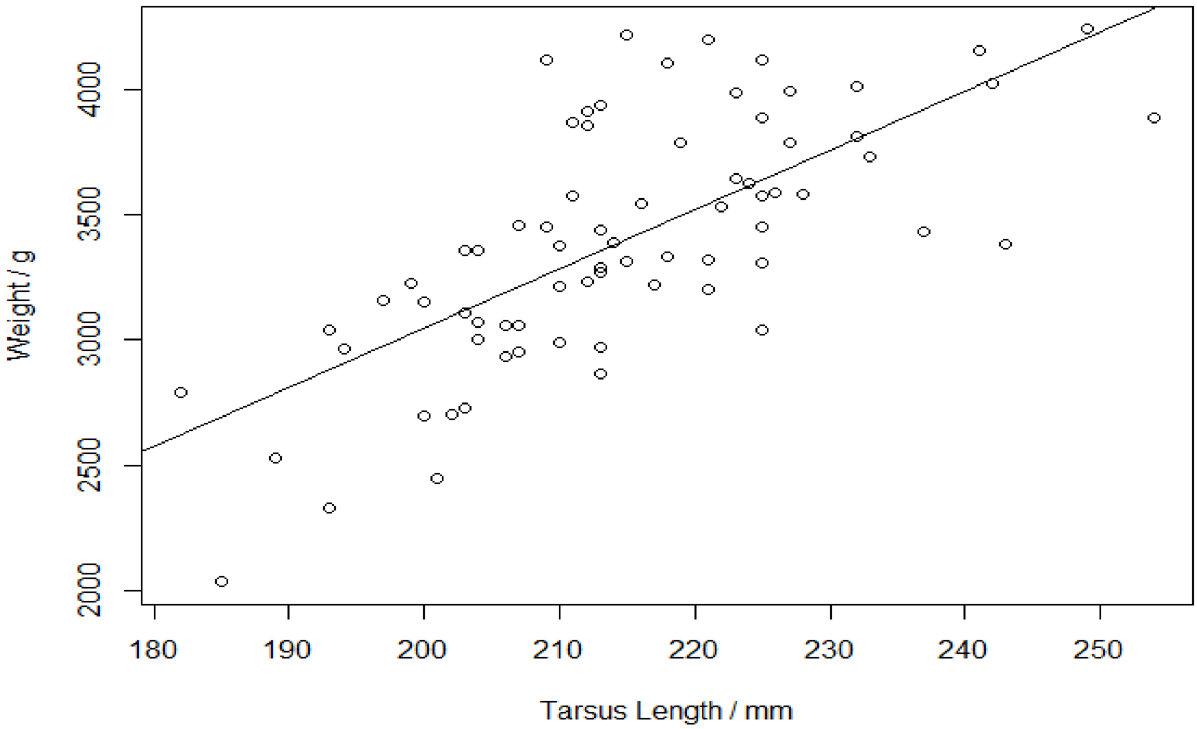


Figure 5. Weight by Tarsus Length of juvenile white storks measured in southern Portugal during 2016 and 2017. Weight residuals by given tarsus length were used as the Tarsus Weight Index BCI.

Table 1. Summary of data, their sources, types and units used in this project. Raw data came from physical readings, measurements and observations, calculated metrics were calculated using combinations of all others.

Predictor and Dependent variables were used in statistical analysis.

Description	Unit	Data Type	Variable
Nest Location	x y	Raw	
Landfill Location	x y	Raw	
Distance from Nest to Landfill	km	Calcualted	Predictor
Morphological			
Bird Weight	g	Raw	
Wing Length	mm	Raw	
Tarsus Length	mm	Raw	
Weight by Wing Index	g/mm	Calcualted	Dependent / Predictor
Weight by Tarsus Residual Index	g	Calcualted	Dependent / Predictor
Migratory			
Bird Location	x y	Raw	
Bird Speed	m/s	Raw	
Mean Speed Day or Leg	m/s	Calcualted	Dependent
Bird Altitude	m (above ellipsoid)	Raw	
Mean Altitude AMSL Day or Leg	m (AMSL)	Calcualted	Dependent
Date - Individual Reading	Gregorian Date H:M:S	Raw	
Date - Leave Nest	Julian (Day of Year)	Calcualted	Dependent
Date - Leg Boundaries	Julian (Day of Year)	Calcualted	Dependent
Date - End Migration	Julian (Day of Year)	Calcualted	Dependent
Distance Actual Day or Leg	km	Calcualted	Dependent
Displacement Day or Leg	km	Calcualted	Dependent
Efficiency per Day or Leg	%	Calcualted	Dependent
Migration Day	Days	Calcualted	Dependent
Stop Over Day	Days	Calcualted	Dependent

Results

Means of wing length and TWI were significantly higher in 2017 than 2016 (Table 2), but the means of the other three morphometrics were similar between years. The greater wing length could indicate that the birds measured in 2017 were older at logger deployment. The wing length is not considered alone in analysis but is accounted for in the WWI, and this does not vary by year. As the annual weight means were similar, the increased TWI could be related to increased age. As I am considering the relationship between landfill proximity and morphological and migration metrics of individuals, I shall use the combined dataset (Table 3) for further analysis and note the potential effect of year if relevant.

Both WWI and TWI were significantly higher in birds that recorded an outward migration than in those that did not. For birds that did not migrate, no difference was found between the means of those that left the nest and those that did not, as shown by (Table 4) and (Figure 6). There was no variation in means by year of the three categories.

Weight, tarsus length and both BCI's all increased significantly with reducing distance between nest and landfill (Table 5) and (Figure 7).

Linear models, analyses of variance and Tukeys Post Hoc tests were used to compare BCI variance with the number of siblings in a nest, but no significant difference was found.

Table 2. Range, means and significant difference in means by year, of physical measurements and calculated BCI's of juvenile white storks fitted with data loggers in 2016 and 2017.

Metric	2016 Range	 Mean	 n	2017 Range	 Mean	 n	Difference in Means p
Weight/g	2330 - 4155	3354.4	41	2035 - 4240	3451.97	32	0.418
Tarsus Length/mm	182 - 254	217.1	41	185 - 249	211.88	32	0.117
Wing Length/mm	**304 - 498**	**434.1**	**41**	**411 - 512**	**453.09**	**32**	**0.020**
Wing Weight Index	5.01 - 11.54	7.81	41	4.51 - 10.27	7.64	32	0.571
Tarsus Weight Residual Index	**-677 - 580**	**-96.87**	**41**	**-659 - 855**	**123.93**	**32**	**0.009**

Table 3. Combined maximum, minimum and means of physical measurements and calculated BCI's of juvenile white storks fitted with data loggers in 2016 and 2017.

Metric	Maximum	Minimum	Mean	Standard Deviaton	n
Weight/g	4240	2035	3397	479.76	73
Tarsus Length/mm	254	182	214.8	14.18	73
Wing Length/mm	512	304	442.5	36.29	73
Wing Weight Index	11.54	4.51	7.73	1.28	73
Tarsus Weight Residual Index	854.79	-677.4	-0.08	346.21	73

Table 4. Result of Welch's t-test on the difference in means of Body Condition Indices of juvenile white storks, based on whether the bird migrated, did not migrate or did not leave the nest area (70km radius).

Metric	Migrated	Left Nest - Not Migrated	Not Left Nest	t	df	p
	n=24	n=32	n=17			
Wing Weight Index	**8.30**	**7.52**		**2.46**	**53.96**	**0.017**
	8.30		**7.33**	**2.64**	**30.33**	**0.013**
		7.52	7.33	0.49	35.03	0.620
Tarsus Weight Residual Index	**170.78**	**-86.54**		**2.90**	**53.04**	**0.005**
	170.78		**-78.53**	**2.58**	**34.54**	**0.014**
		-86.54	-78.53	0.08	37.44	0.935

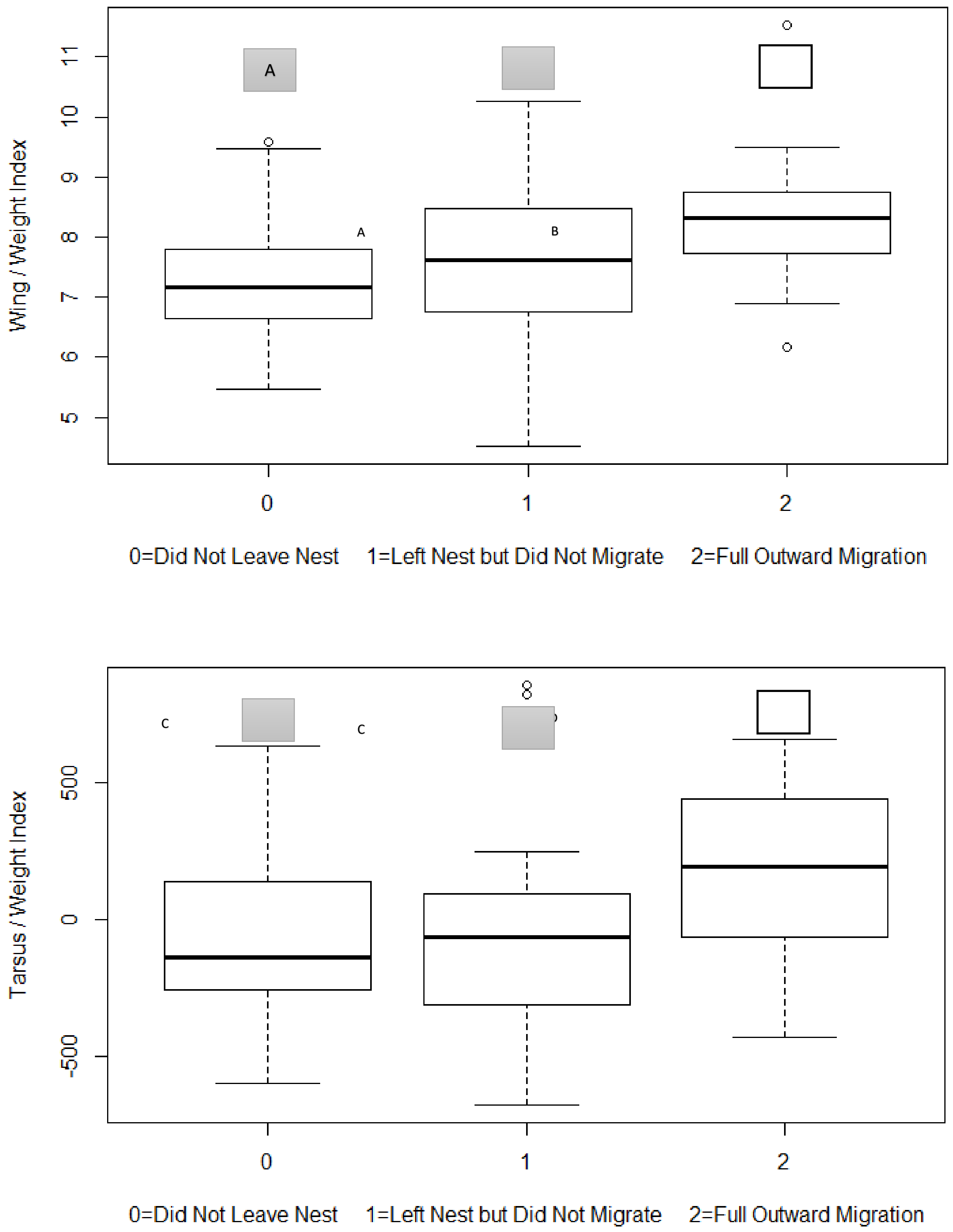


Figure 6. Wing and Tarsus Residual to Weight Indices for juvenile white storks, split by whether they completed a migration from Portugal to sub-Saharan Africa, left the nest but did not migrate or did not leave their nest. Thick line = median values, box and whiskers = quartiles, outliers shown. Letters above plots indicate factors with significant differences in means.

Table 5. Results of linear regression models between juvenile white stork morphometrics and the distance from the nest to the nearest landfill site (km).

Metric	α	β	R^2	p
Weight	3749	-19.13	0.16	<0.001
Tarsus Length	221.2	-0.35	0.06	0.035
Wing Weight Index	8.6	-0.05	0.14	0.001
Tarsus Weight Index	201.06	-10.93	0.10	0.006

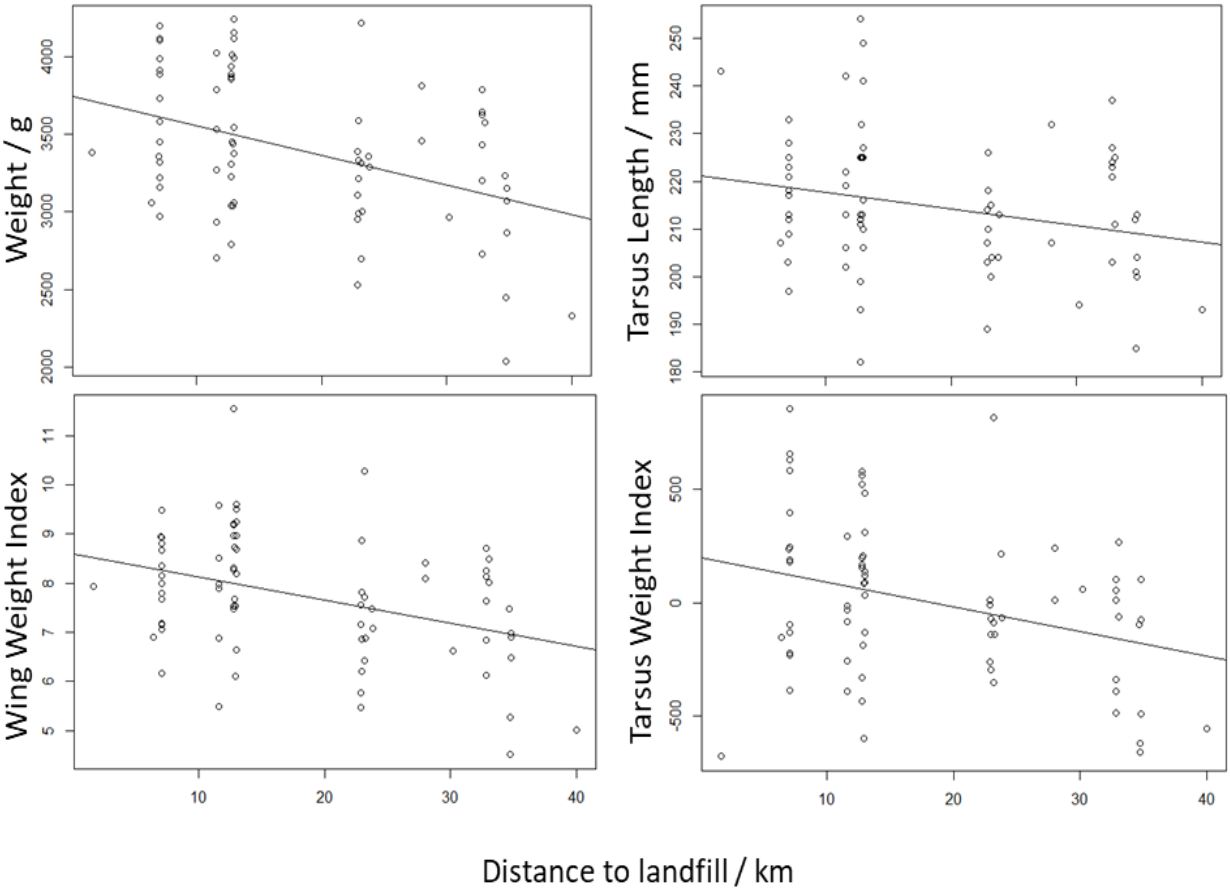


Figure 7. Weight, tarsus length, wing-weight index and tarsus-weight index of juvenile white storks in southern Portugal as factors of distance of nest from landfill site.

All were significantly higher with reduced distance to landfill.

For the 24 birds that recorded an outward migration, neither the total number of days taken to complete the migration nor the number of stop over days during the entire migration differed with proximity to landfill or either BCI**Error! Reference source not found.**.

Only 12 of the 24 outward migrants registered a successful return across the Sahara, and of these, 6 came from nests near and 6 far from landfills.

Table 6 gives summaries of all migration metrics and significant p values of linear models run between each individual predictor and response variable.

Table 6. Summarised migration metrics of the first outward migration of juvenile white storks from Portugal to sub-Saharan Africa in 2016 and 2017. Significance of linear regression relationships between predictor and response are shown. Details about the significant interactions are given in text.

							Distance to Landfill	Wing Weight Index	Tarsus Weight Residual
		Minimum	Maximum	Mean	SD	n	p	p	p
Migration Days	Total	14	71	40.35	18.98	23	ns	ns	ns
	Leg 1	1	59	20.17	19.14		ns	ns	ns
	Leg 2	2	37	10.33	10.01		ns	ns	0.029
	Leg 3	4	13	8.7	2.12		0.018	ns	ns
Stopover Days	Total	0	54	25.96	17.61	23	ns	ns	ns
	Leg 1	0	54	17.58	18.31		ns	ns	ns
	Leg 2	0	31	6.54	9.12		ns	ns	0.034
	Leg 3	0	5	0.78	1.24		ns	ns	ns
Distance - Daily Displacement	Summed Per Bird	2619	3708	3124.51	310.15	22	ns	ns	ns
	Leg 1	241	1090	531.41	244.05		ns	ns	ns
	Leg 2	523	1142	834.68	191.94		ns	0.031	ns
	Leg 3	1302	2271	1758.42	283.01		ns	ns	ns
Distance - Actual	Summed Per Bird	2974	6811	4713	949.91	22	ns	ns	ns
	Leg 1	292	1339	626.87	267.16		ns	ns	ns
	Leg 2	595	3197	1295.31	674.56		ns	ns	ns
	Leg 3	1764	4686	2795.62	657.47		ns	ns	ns
Efficiency - Daily/Leg	Summed Per Bird	1.99	2.78	2.42	0.21	22	ns	ns	ns
	Leg 1	0.39	1.00	0.72	0.18		ns	ns	ns
	Leg 2	0.71	0.98	0.87	0.09		0.047	ns	ns
	Leg 3	0.69	0.95	0.83	0.07		ns	ns	ns
Efficiency - Actual/Daily	Summed Per Bird	5.79	12.48	9.97	1.69	22	ns	ns	ns
	Leg 1	0.30	0.91	0.69	0.17		ns	ns	ns
	Leg 2	0.13	0.96	0.69	0.22		ns	ns	ns
	Leg 3	0.08	0.97	0.70	0.19		ns	ns	ns
Mean Altitude - AMSL	Total Mean	782.1	1632.8	1276.2	202.70	22	ns	ns	ns
	Leg 1	465.2	880.6	639.5	117.75		ns	ns	ns
	Leg 2	857.0	2219.0	1476.0	347.41		ns	ns	ns
	Leg 3	1221.0	1870.0	1519.0	178.63		ns	ns	ns
Mean Speed - km/h	Total Mean	40.22	48.45	44.87	1.99	22	ns	ns	ns
	Leg 1	38.51	48.00	42.89	2.53		ns	ns	ns
	Leg 2	38.65	52.25	44.62	3.01		ns	ns	ns
	Leg 3	42.38	51.76	46.46	2.85		ns	ns	ns

Migration Leg 1 - Nest to Strait of Gibraltar

Of the 73 tagged storks, 56 recorded a night spent more than 70km from their nests, and for these 56, the first night spent away occurred later in the year the closer the nest was to a landfill ($\beta=-0.685$, $p=0.005$, $R^2=0.14$), representing almost one week later for every 10km closer (Figure 8). No significant relationship was found between the leaving date and either of the BCI's. Only 43 birds recorded a crossing of the Strait of Gibraltar, and the date that they did so correlates with the date that they left their nest (Pearson=0.48, $p=0.001$) (Figure 9). Similar to the leave nest date, the crossing date is later in the year with reduced distance to a landfill, ($\beta=-0.826$, $p<0.001$, $R^2=0.25$), and again does not vary significantly as a factor of either BCI. Interestingly, neither the number of migration or stopover days spent on the Iberian Peninsula varied in relation to any of the predictors.

The leave nest date showed significant difference with varying nest latitude ($p=0.044$), but when run as part of a GLM in conjunction with landfill distance, latitude was no longer significant ($p=0.47$). Further inspection revealed that all nests in the southernmost colonies were situated closer than 15km to a landfill, and as such the latitude significance could be attributed to landfill proximity.

A model was run using wing length alone, to see whether this, as a proxy for age, affected the leave date, which it did not ($p=0.93$).

The leave nest date showed no significant difference whether an outward migration was completed or not ($t=0.641$, $df=53.987$, $p=0.52$).

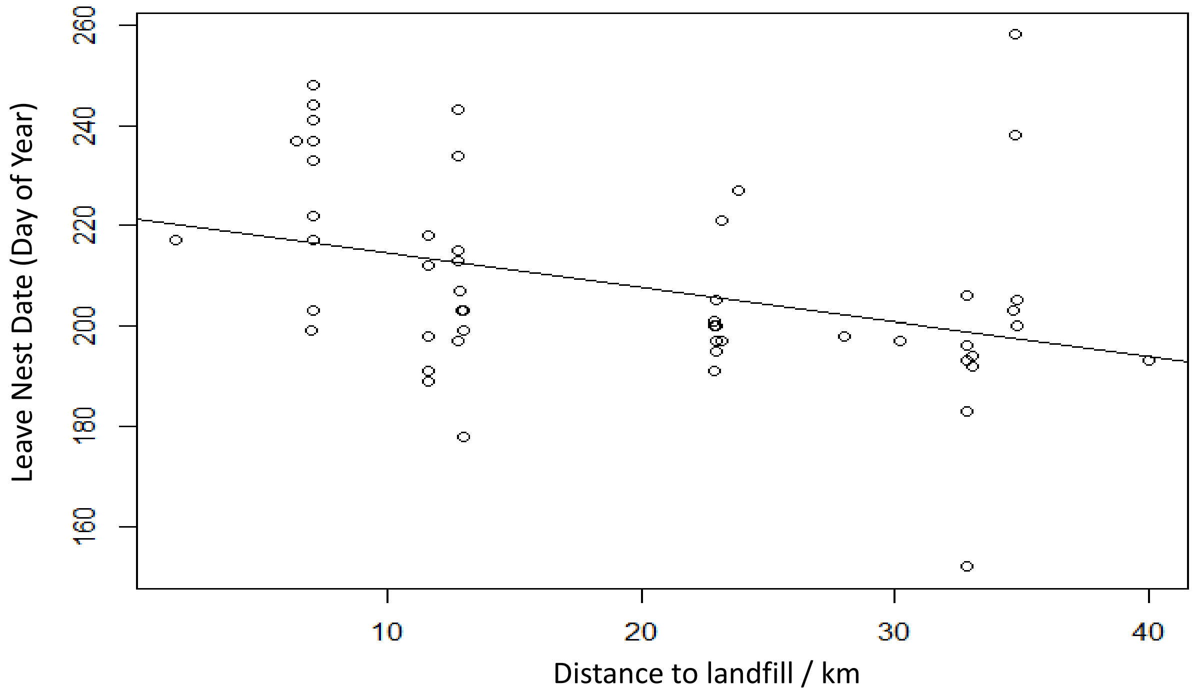


Figure 8. First date that a juvenile stork overnights at more than 70km from their nest, as a function of nest distance from landfill.

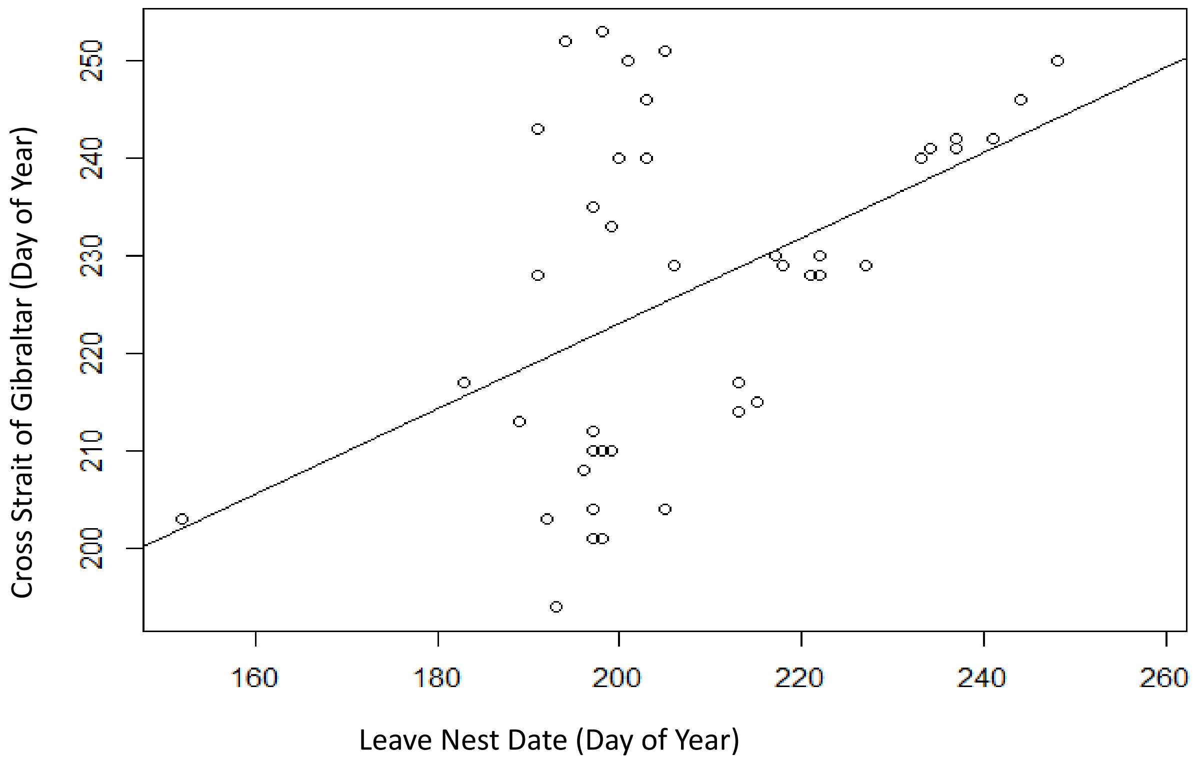


Figure 9. Correlation between leaving nest date and the date of crossing the Strait of Gibraltar by juvenile storks.

Migration Leg 2 – Mediterranean to Sahara

Within this leg, each of the three predictors has a significant relationship with just one response variable, and no response variable differs significantly in line with more than one predictor. Birds from closer to landfills cross more efficiently (leg displacement over summed daily displacement) (α=0.938, β=-0.004, R^2=0.18, p=0.047), birds with higher WWI's travel fewer kilometres (α=1528.43, β=-83.29, R^2=0.21, p=0.031) and birds with higher TWI's spend fewer days (α=12.84, β=-0.15, R^2=0.20, p=0.029), (Figure 10).

Mean and maximum height above mean sea level through this leg did not vary significantly with any of the three predictors.

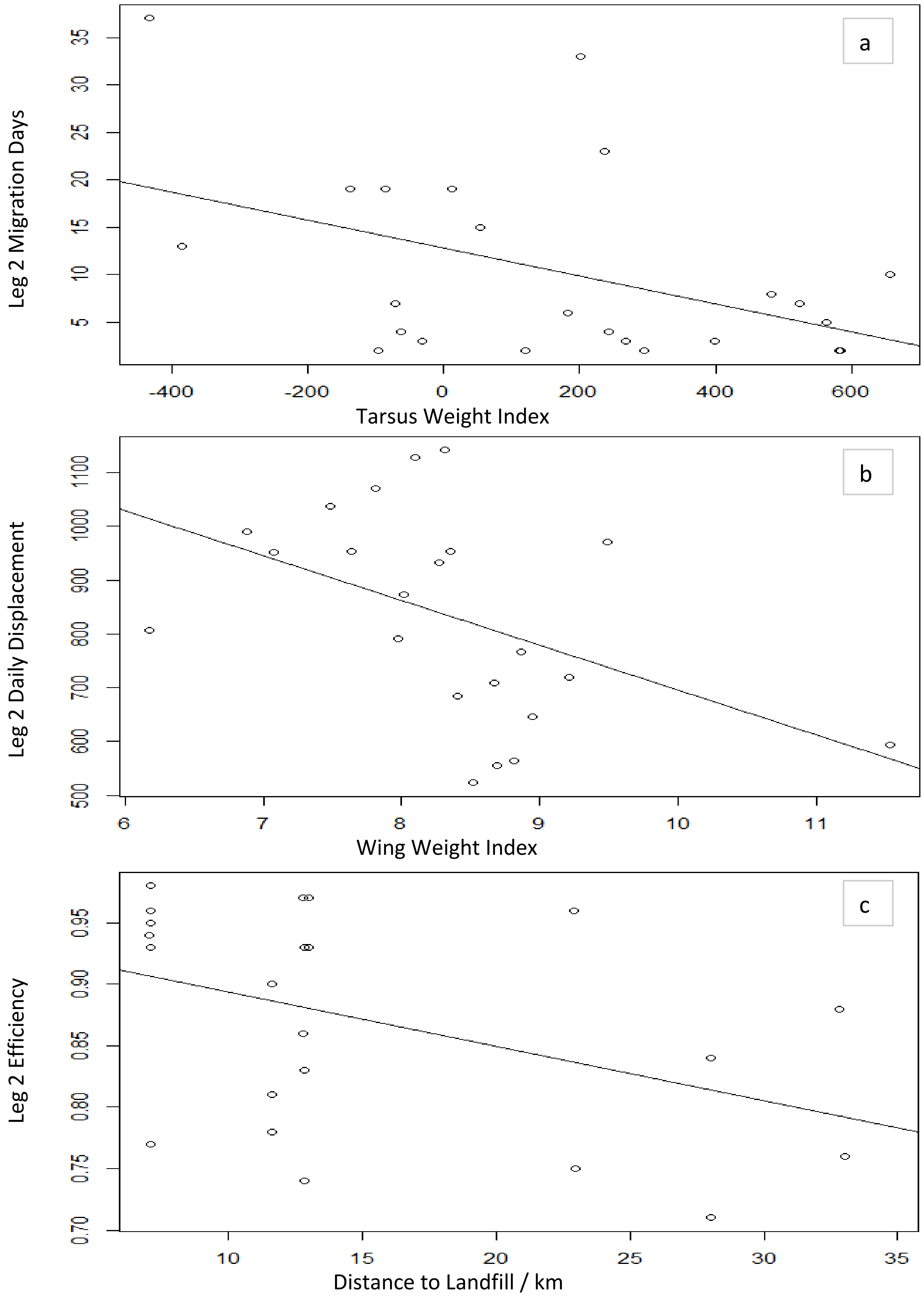


Figure 10. a- Total number of days spent between Gibraltar and the Sahara as a function of TWI.
b- Summed daily displacement of migration days (those with displacement >70km) between Gibraltar and the Sahara as a function of WWI.
c- Efficiency of migration (daily/leg displacement) between Gibraltar and the Sahara as a function of nest distance to landfill.

Migration Leg 3 – Northern Sahara to Migration End in the Sahel

The number of days spent travelling through this leg are fewer for birds raised farther away from a landfill (α=10.50, β=-0.11, R^2=0.24, p=0.018), but do not change with either BCI. The number of stopover days in this leg are negligible and have no relationship with any predictor. Neither the leg nor summed daily displacement, efficiency, speed or height above mean sea level for this leg differed significantly with any of the predictors.

The longitude at which a stork entered the Sahara did not vary significantly with any predictor, but the farther the nest was from a landfill the more west the exit point at 20°N was (α=-4.26, β=-0.22, R^2=0.35, p=0.004, Figure 11). Those from nests near to a landfill (less than 15km) finished farther east and those from nests far from landfills (more than 15km) finished farther west than their entry points (t=3.57, df=9.58, p=0.005, Figure 12). The leave nest date also had a significant relationship on the change of longitude, with later leavers finishing farther east of entry point (α=-17.08, β=0.08, R^2=0.20, p=0.036), but had no bearing on the exit longitude alone. The effect of year on entry, exit and change in longitude was considered alone and as a covariate in a linear model and as a random effect in a mixed model and was found to have no significance in any way.

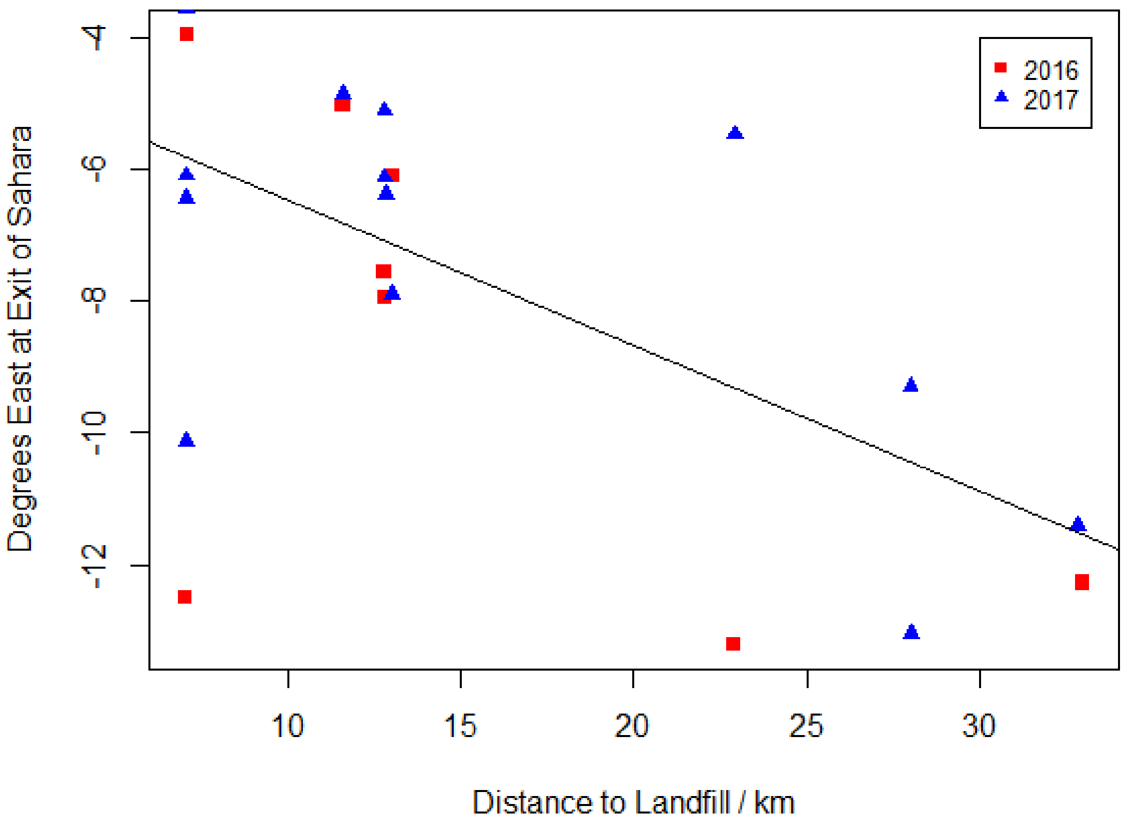


Figure 11. The Degrees East of Prime Meridian at which juvenile storks on their first migration from Portugal, exited the Sahara (20°N), as a function of the nest distance to landfill. Negative numbers denote degrees west of the Prime Meridian.

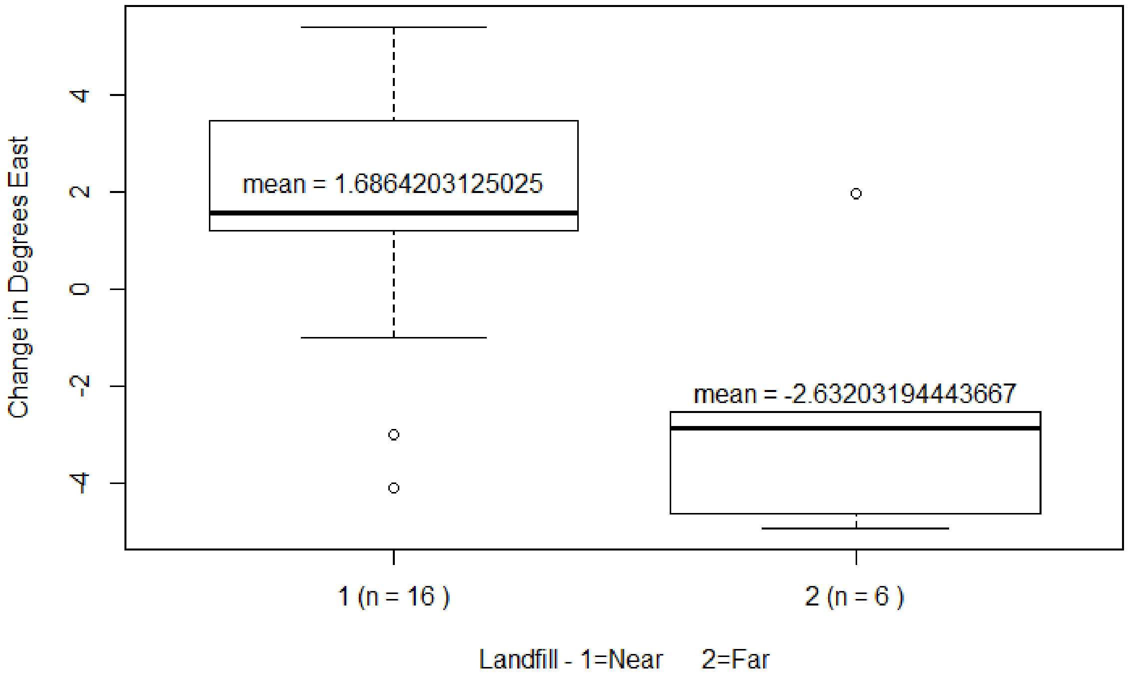


Figure 12. Change in longitude between point of entry (at 30°N), and exit (at 20°N) of the Sahara by juvenile storks during their first migration from Portugal to the Sahel.
Thick line=median, box and whiskers=quartiles, outliers shown.

Discussion

Experiment Design

The need for birds to be physically removed from and replaced into their nests required that nest selection was limited to those that were within approximately 3m from ground level and could be easily accessed, which causes the potential bias that lower nests provide better or worse conditions than higher. This was measured and taken into consideration as far as possible, by using camera poles and drones to count the number of eggs and chicks in higher nests. Although the physical size and survival rate could not be measured, no difference was found in egg and chick numbers between nests of varying heights (Rogerson, pers comms.).

Variation in Morphometrics

Physical measurements of individual storks were taken, with the idea that an indication of relative fitness and body condition could be ascertained from them. Body condition usually refers to the amount of muscle and fat available to an individual beyond that of the basic body structure (Green, 2001). Direct measurements can in themselves be used as indicators, but the juveniles were not all the same age when measured, and therefore at slightly different stages of development, which could cause some variance in size. Body Condition Indices calculated as residuals or ratios attempt to provide an adjusted mass to account for some externalities (Heath, Strasser, Foster, Bardo, & Bird, 2011). In this instance, wing length was found to be the best morphological indicator of age (personal communications, Rogerson) and the WWI was created to provide an age-related account of variations in weight. Tarsus length was higher the nearer a nest was to a landfill, but the very low R^2 value of 0.06 in this model indicated that tarsus length variation could be by large part, a natural variation among individuals, and the TWI provides some account of weight variation due to natural variations of body size within populations. Whilst BCI's have been commonly used, their true representation of fitness has been poorly studied (Heath et al., 2011) and many other factors may also influence the univariate measurements instead of or in addition to condition. Some influences to weight include, the time since last feeding (Wiklund, 1996) and feather growth and mass (Newton, 2008). The age-related feather mass variance could be partially accounted for in the WWI, but the effect of time since least feeding has not been accounted for. Although not measured or included in any way, it would not be unreasonable to draw the conclusion that birds farther from landfills would be fed less frequently. Greater distances could increase travel time for parents on food collection runs, and therefore increase the time between, and reduce the number of feeds due to effort vs reward required by the parents.

The relationship between age and weight is more logistic than linear in white stork nestlings, with a levelling off or even slight reduction in weight as they near fledging (Tsachalidis, Liordos, & Goutner, 2005). In-nest activity increases as birds jump around and practicing wing flapping to strengthen and learn control of flight muscles, and this increased activity potentially causes a stabilisation in weight. The exact age of the bird is not known in this study but as all birds were relatively similar in terms of development stage, all weight and size increases have been assumed to be linear.

One of the largest influences on body size variation is an individual's sex, where males will frequently be noticeably different to, and vary at different ages and rates to females. In this study the sex of the individuals was unknown and could not be accounted for and may be the cause of some differences or lack thereof within analysis.

The use of BCI's may not be an ideal method of determining fitness or of providing perfect variables for use in further analysis, but I believe that they have provided a useful tool in this study and the results found by their use can be taken as a sound starting point to guide future studies. Whether direct or indexed measurements for size are used, and in keeping with the findings of Plaza & Lambertucci (2017), there seems little doubt that birds raised closer to a landfill tend to be larger than those from farther away.

Do Birds Leave Their Nests Later?

There is a strong indication that birds raised closer to landfills leave later. One of the prime causes of migration is to move to a place with better conditions based on a seasonal reduction at the current location, but with landfills providing a consistent supply of resources, there is a reduced incentive to do this. This goes hand in hand with the premise that PAFS are altering migration characteristics of the white stork (Gilbert et al., 2015). Further to the influence on migration dates in general, is the premise that as resources get less and juveniles grow bigger, the effort required by the parents to feed them becomes counterproductive. Thus, as the breading season comes to an end, parents may reduce resource provision to their young to the point where the young are forced to leave in order to find more food for themselves. However, in a situation where food supply is plentiful and consistent, the need of the parents to reduce their provisioning and encourage fledging can be greatly reduced, resulting in a much later leave nest date. Possibly to the point where the juveniles and parents leave together on migration. The timing of parents and juveniles start of migration from the same nest is another aspect for future research.

The influence of nest latitude on the leave nest date at first seemed significant, but further examination showed that all nests in the southern part of the region were closer than 15km to a landfill, and as such this biased the results, and the latitude factor was not considered any further.

Do Birds Have Different Migration Metrics?

This study obtained migration data from 24 of 73 tagged storks and calculated an average migration to have 14.3 move days, displacing 203.7km each day, at an average speed of 12.4m/s. When variations in route and definitions of move days (100km vs 70km) are considered, these parameters compare favourably with (Rotics et al., 2016) on their study of stork migrations from Germany to the eastern Sahel (average migration 14.8 days displacing 271.4km at 13.2m/s.).

We cannot assume that the data received is inclusive all the storks that migrated, as despite evidence that at least 14 birds died within 70km of their nests, some transmitters are also known to have stopped working. In one such case, a bird was positively identified on a landfill, two months after the last logger data had been received. Although unlikely, there is a possibility of some migration data not being included in analysis and, a possibility that missing migration data could marginally impact some findings. Death and full migration are two potential outcomes for a juvenile, but partial migration is also possible, and some birds will stay within Iberia or Morocco. This may occur because they are either too weak to migrate further or conditions and resources there appear sufficient to sustain them for the winter. Despite the possible missing data, birds with higher BCI's seem to complete full migrations far more than those with average or low BCI's, but there seems little difference in the size of birds that either die or overwinter north of the Atlas Mountains.

The overwinter use of breeding season nests and landfills within Iberia is documented by Gilbert et al., (2015), and it is interesting to note the possibility that those that do not migrate may be the weaker ones. Perhaps if the extra resources supplied by the landfill were removed, then these potentially weaker individuals would die before or during the winter period.

Speed, height, distance, efficiency and time differed surprisingly little with any of the predictor variables, with the primary exception being in leg 2. Here the individual relationships between one predictor and one response were small but significant, and each significance indicated that larger birds from closer to landfills performed ‘better’ in terms of time, distance and efficiency. There are likely other factors at play here, and alternative or more accurate predictors may provide more definitive results, but that three differences, all indicating a similar principle were found, strengthen the individual results, which on their own could be taken as a chance occurrence.

The lack of variation going through leg 3 falls in with findings of (Liechti, Ehrich, & Bruderer, 1996), who found that storks are fairly uniform in migration performance and do not alter their flight behaviour or improve their speed with varying conditions. The most surprising result was the difference in days taken to cross the Sahara, where birds from closer to landfills take longer to cross. This counterintuitive outcome led to further analysis, where differences of easting in terms of change in and exit longitude were found. This was not originally considered as a question of this study, and no definitive reason as to why it occurs can be given, but I have noted several thoughts and hypotheses on the matter. The first is that this is just chance, and nothing can be read into or derived from the findings. Secondly, white stork juveniles usually migrate within flocks of adults, taking their direction, pace and altitude from the lead adults (Flack, Nagy, & Fiedler, 2018), and a case of ‘follow the leader’ could have resulted not only in the difference of easting, but also in the lack of difference within other metrics. Thirdly, easting change varies similarly with both distance to landfill and the leave nest date, but not with the date of crossing the Strait of Gibraltar. The R^2 of the landfill distance model is much higher than that of the nest date (0.33 and 0.20 respectively), implying that the landfill distance is more influential than the date of leaving the nest. Lastly, in a study of honey buzzard migrations, (Vansteelant et al., 2017) note the wind conditions across the Sahara to be a potential defining factor in determining the exit longitude of migrant birds, with 49% of longitudinal variance in their study being attributed to wind conditions. In truth it is probably a combination of several of these factors, and as the largest defined migration variance with relation to landfill distance, I feel this would be an interesting topic for further research.

Conclusion

In considering the difference in morphology of pre-fledge white storks, and their subsequent first migration metrics, there is a strong indication that larger birds migrate more successfully than smaller. There also seems little doubt that birds raised closer to landfills are in some measure larger than those raised farther away, there is however no distinct correlation between birds raised closer to landfills migrating more successfully.

Although some significant differences were found in migration metrics based on their home nest distance from landfill, they were small and not likely to alter the survival or success of the species. The influence of landfills in Europe and Africa after the juveniles have left their nest, along with a more in-depth look at body condition on migration metrics, could be examined as part of a longer research project.

In closing, I believe that the removal of PAFS from European landfills will have a negative impact on the European population numbers of white storks, but that this will predominantly be on resident populations. I do not believe that migrants will be overly hampered by that particular act alone. Overall, populations will need to be closely monitored, and contingency plans devised and readied for rapid implementation should numbers start dropping too drastically.

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