



OPEN Community science as a potential tool to monitor animal demography and human-animal interactions

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Community science can provide crucial insights into population dynamics and demography. To date, its effectiveness for understanding human-wildlife interactions has not been tested. This is vital for designing effective wildlife management plans. We used a case study of an individually marked population of mute swans *Cygnus olor*, to test the reliability of community scientist data for quantifying self-reported interactions. We compared 5,251 community scientist sightings of individually marked birds with 317 observations recorded through systematic recording methods, to test the reliability of sightings, and of self-reported human-swan interactions. 98.86% of ring readings were correctly reported; sighting reliability increased with experience and was higher when the observer fed the birds. Community scientist observations were reliable for quantifying family group size, but not clutch size. Self-reported data for assessing feeding interactions with wildlife were not comparable with systematic recording methods. 22% of standardised observations recorded supplementary feeding of swans by people. This is the first systematic quantification of the frequency of interaction of wild waterfowl with humans through supplementary feeding in the Northern hemisphere; we highlight potential impacts of this common human-wildlife interaction for both birds and people. We provide new insights into using community science methods as potential alternatives to more time-consuming systematic methods. Community science methods may be useful across a range of systems where humans and wildlife interact, but we highlight the need for validation of the reliability of community scientist data, particularly self-reported behaviours, before being used to inform management and conservation practices.

Keywords Citizen science, Behaviour, Supplementary feeding, Wildlife, Mute swan, *Cygnus olor*

Wildlife monitoring provides crucial insights into animal population dynamics (e.g., abundance and distribution) and animal demography (e.g., birth, death), which informs animal management/conservation policies and laws¹. However, to date, animal monitoring has generally neglected to collect data on human-wildlife interactions, which is vital for designing effective conservation plans². Animal monitoring through community science (or citizen science), where members of the public report their sightings, can be highly beneficial in terms of data gathered as well as for the people involved (e.g., increasing public awareness, acquiring new skills, and increasing conservation efforts)^{3–5}. Therefore, community science could be a potential powerful tool to assess animal population dynamics, demography and human-wildlife interactions. This is especially relevant for the wide range of species that live closely alongside humans, because the actual impacts of human activities on animals remain poorly understood⁶, and technological advances such as the use of artificial intelligence (AI) to identify individual animals^{7,8} have huge potential to involve community scientists in collecting such data.

Community science is increasingly used as an effective tool in conservation, for both building scientific knowledge and encouraging public action through education^{9,10}. Community science monitoring is particularly useful for animal species which are difficult to follow such as birds with wide distributions¹¹. Broad-scale citizen science platforms and projects, such as eButterfly¹² and eBird¹³ in the US and the British Trust for Ornithology Breeding Bird Survey in the UK¹⁴, enable members of the public to record their own observations and contribute

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to national-scale wildlife monitoring programmes, whose data are then used alongside other datasets by researchers to address conservation-relevant questions^{15,16}.

One of the most widespread and pioneering programmes is bird ringing, the results of which feed into national monitoring and targeted conservation actions, with many countries operating a nationally co-ordinated ringing scheme¹⁷. These projects often rely on community scientists reporting their sightings of individually colour-marked birds to the project co-ordinator for each separate project, and colour-ringing can lead to increases in the number of reported observations of up to two orders of magnitude over that of metal rings alone¹⁷. These data then feed in to local and national scale analyses of demographic parameters¹⁸. In the UK, there are ~800 active colour ringing projects registered on the European colour-ring birding website¹⁹, most of which record the presence of a colour marked individual, allowing inferences of distribution and movements. Sightings can be reported by both trained and untrained observers, with trained observers having a 19% lower misread rate than untrained observers in a study of White Storks *Ciconia ciconia*²⁰. Quality of optics, and the background colour of rings can also affect the accuracy of colour ring resighting reports, with some letters having higher reporting error rates than others²¹. What is not known is how many birds are seen and not reported due to uncertainty around the reading of the ring, and what might influence this. Less invasive techniques, such as the use of AI to identify individuals from photographs^{7,8,22}, also has huge potential to harness the power of community science across a range of wildlife species; from primates such as the Japanese macaque *Macaca fuscata*⁸, to uniquely patterned species such as tigers *Panthera tigris* and jaguars *Panthera onca*⁷, to multiple externally un-marked small bird species²².

Most, if not all, colour ringing reports provide the date, ring number and location of sightings, but the collection of demographic data (e.g. nesting parameters) linked to colour ringing data is sparse²³. To date, animal demography and human-wildlife interaction data are mostly gathered by trained researchers, limiting the numbers of observations recorded, particularly in species with wide distributions²⁴. However, while validity assessments have been conducted on community science projects related to population dynamic monitoring^{24,25}, there is currently limited evidence as to whether some specific data, such as demographic and human-wildlife interactions, can reliably be recorded by untrained members of the public²⁴.

Humans seem to have a strong proclivity to interact with wildlife, with recreational activities such as wildlife watching and feeding growing rapidly²⁶. These activities involving wildlife can have significant benefits for humans, and are important for connecting people to nature—especially in urban settings—and for human mental health^{27,28}. This seemed especially relevant during the Covid-19 pandemic where lockdowns provided limited human social interactions, and were linked to an increase in human recreational use of urban natural environments²⁹. Despite the potential benefits of these interactions to both humans and wildlife (e.g. ecological awareness, food provision), growing research has also highlighted serious concerns for animal welfare and public health^{30,31}.

In particular, previous research has provided evidence that supplementary feeding of wildlife has diverse impacts on wildlife health across a range of species^{32–35}. Dietary changes in wildlife linked to the availability or provision of anthropogenic food can impact body condition^{36,37}, productivity³⁸, and population size³⁹, among other metrics⁴⁰. Supplementary feeding of wild birds generally involves feeding in gardens⁴⁰, but can also involve the targeted feeding of specific birds or families in parks or the wider countryside⁴¹. Such feeding may result in negative impacts when birds select easily accessible and low quality food (i.e. “junk food”) over high quality food that may take longer to find, leading to nutritional restrictions^{42,43}.

The frequency and nature of the unregulated feeding of wild birds—especially outside a garden setting—is rarely quantified, and consequently implications for wild bird health are largely unknown⁴¹. Food provided in gardens tends to be a reliable resource that birds can decide when to visit to optimize their energy reserves⁴⁴. However, food is often also provided on a more ad hoc basis, whereby specific individuals or families of birds are targeted for food provisioning by members of the public. For example, the feeding of waterbirds in public parks and along waterways is a common and widespread activity, although rarely quantified⁴¹, and seems likely to vary with environmental variables such temperature and rainfall, with feeding more likely during clement weather conditions. Impacts of unreliable supplementary feeding may differ from those of predictable feeding. Where precocial young learn feeding behaviour that are relevant for supplementary food rather than natural food resources from their parents, this has the potential for long-term detrimental impacts on individual health and condition should this food source become unavailable⁴⁵.

Mute Swans (*Cygnus olor*) are a widespread and common waterbird species across Europe, and have been widely introduced worldwide. They are often the target of human-animal interactions involving supplementary feeding^{46–48}, although this is rarely quantified (but see Chapman & Jones⁴¹ for a quantification of duck feeding in Australia). Much research on UK mute swans has focussed on investigated lead poisoning as the major identified driver of mute swan population decline in the UK. Since lead use has been regulated, the UK mute swan population is estimated to be stable⁴⁹. However, there remains much variability in local population trends, with food supply, habitat quality and winter temperatures all thought to influence distribution^{49,50}. However, any quantification of, or potential impacts of, supplementary feeding on swan population dynamics or health, are lacking.

Here, we use a colour marked population of mute swans *Cygnus olor* in the city of Lincoln, UK, to explore whether data from community scientists can be reliably used to identify individual birds through colour ring resightings, to quantify demographic parameters during breeding, and to estimate the extent of human-swan interactions such as supplementary feeding. We designed and implemented a project using the EpiCollect5 App⁵¹, advertised through local press, to recruit citizen scientists to record these data through the Lincoln Swan Project, using methods that could be easily applied to other species that regularly interact with or are seen by people, and here we assess the data quality from the first three years of the project. Specifically, we use these data, alongside standardised behavioural observations of the same birds to ask:

1. How reliable are community scientist data on colour-ring readings and breeding parameters?
2. What influences the certainty in ring reading and the likelihood of community scientists reporting a ringed bird?
3. Can self-reported community science data allow us to reliably quantify human-animal interactions?

Results

Data consisted of 3,752 individual sightings (some containing multiple ring numbers) submitted between 28th April 2020 and 26th June 2023, of 195 individual birds. From the 90 community scientist data collectors who signed up to the project, 42 had submitted sightings (including nine trained project researchers; hereafter: trained researchers, and 81 community scientist data collectors; hereafter: data collectors). Sightings reported per observer ranged from 1 to 846 (mean \pm SE: 89.33 ± 26.68).

From these submissions, 72.8% ($n = 2730$) reported at least one ring number, 6.2% ($n = 234$) reported that the bird was ringed but they could not read the number, 11.8% ($n = 442$) did not know whether the bird was ringed, and 9.2% ($n = 346$) reported that the bird(s) that they observed was not ringed.

Analysis 1: reliability of ring sightings, and family group size reports

The 2,730 reports including ring numbers reported 5,251 sightings of colour-ringed individuals. From these, 59 errors were identified (1.14%). Errors consisted largely of misreads, typos (e.g. mixing L005 and L006), or the reporting of an incomplete ring number (e.g. just the number, not the letter). The number of individual ring reports per observer ranged from 1 to 1,684 (mean \pm SE: 128.07 ± 47.72). Error rates per observer ranged from 0 to 16%. Error rates were non-significantly higher in our trained researcher group ($0.053 \pm 0.020\%$) compared to our data collector group ($0.040 \pm 0.014\%$; GLM, $\text{Dev}_{2,30} = 0.058$, $p = 0.76$), so we included data from all our observers in subsequent analyses.

Once data from 9 observers who submitted fewer than 5 sightings had been removed so as to allow subsequent statistical models to converge, 5,235 sightings from 32 observers remained; the error rate remained at 1.14%.

Error rate differed among observers (Binomial GLM, $\text{Dev}_{5210, 5250} = 107.79$, $p < 0.001$), although error rate per observer was positively associated with the number of submitted sightings (Quasi-binomial GLM, $\text{Dev}_{30,31} = 0.52$, $p = 0.005$; Fig. 1). The error rate for the 50% of observers who submitted the lowest number of sightings was 14 errors in 237 observations (5.9%) compared to 45 errors in 4,998 observations (0.9%) for the 50% of observers who submitted the highest number of sightings.

Family group size data were extracted from 1,676 sighting reports provided by 32 observers between April and August inclusive in 2020–2023, from 27 territories. The number of sighting reports reported per observer during this period ranged from 1 to 416 (50.79 ± 15.56), and per territory ranged from 1 to 227 (62.07 ± 14.36). Once data from territories with fewer than five sightings, and from observers submitting fewer than five records within this period were removed, 1,437 sighting reports of 21 territories from 25 observers remained. Clutch size could not be evaluated from the data as there was rarely any consensus from multiple observers for any given nesting attempt. However, relatively few errors ($n = 27$, 1.9%) were identified in the family group size data once the family had left the nest. Where changes (e.g. reduction in cygnet numbers) were noted, these tended to be consistent and were often accompanied by a comment from the observer to this effect. Excluding data from our trained researchers made no substantive difference to the results of our analyses (Appendix 2).

Analysis 2: assessing certainty in ring reading

Territory identity could be inferred from a combination of location and group size composition from 2,697 records from 30 observers who submitted five or more records, providing data for 25 swan territories with five or more sightings. Certainty in ring reading (whether an observer stated with certainty whether a bird did or did not have a ring, or stated that they could not read the number or did not know whether the bird was ringed) varied among observers, and among territories (Table 1). Certainty differed between years in only the model including Territory ID (Table 1). In both models, sightings involving feeding the birds were associated with a higher certainty than those who did not (Table 1), with 98.9% of those sightings also reporting feeding the birds certain about the birds' ring status, compared to 79.9% of those who did not (Fig. 2). Excluding data from our trained researchers made no substantive difference to the results of our analyses (Appendix 2).

Analysis 3: assessing reliability of quantifying human-swan interactions

To test whether we could use data from the App in assessing the relative proportion of visits to each territory that involved supplementary feeding, we compared 1,693 self-reported App observations with 298 standardised observations, across 12 swan territories. Report type (Observation or App report) strongly influenced the proportion of reports involving supplementary feeding (Table 2), with 50.0% of App reports involving feeding compared to 22.1% of standardised observations (Fig. 3).

When directly comparing estimates for each method at the territory level, we found no correlation between estimates from the App and from standardised observations (Spearman's rank, $S = 308$, $p = 0.81$; Fig. 4).

Given the differences between App reports and standardised observations, we examined each dataset separately to test the factors influencing both self-reported App feeding data, and observed supplementary feeding during standardized observations of swans. Observed feeding events differed between territories, and were more likely to be observed during longer observation periods, but showed no temporal pattern within days or between weekdays and weekends (Table 3).

The proportion of self-reported feeding events reported through the App differed by territory, and in relation to the self-reported duration of the interaction (Table 4), with interactions involving feeding lasting double the length of time than those not involving feeding (Fig. 5). The proportion of interactions involving feeding also varied temporally (Table 4), being marginally higher at weekends than on weekdays (Fig. 6a), and increasing

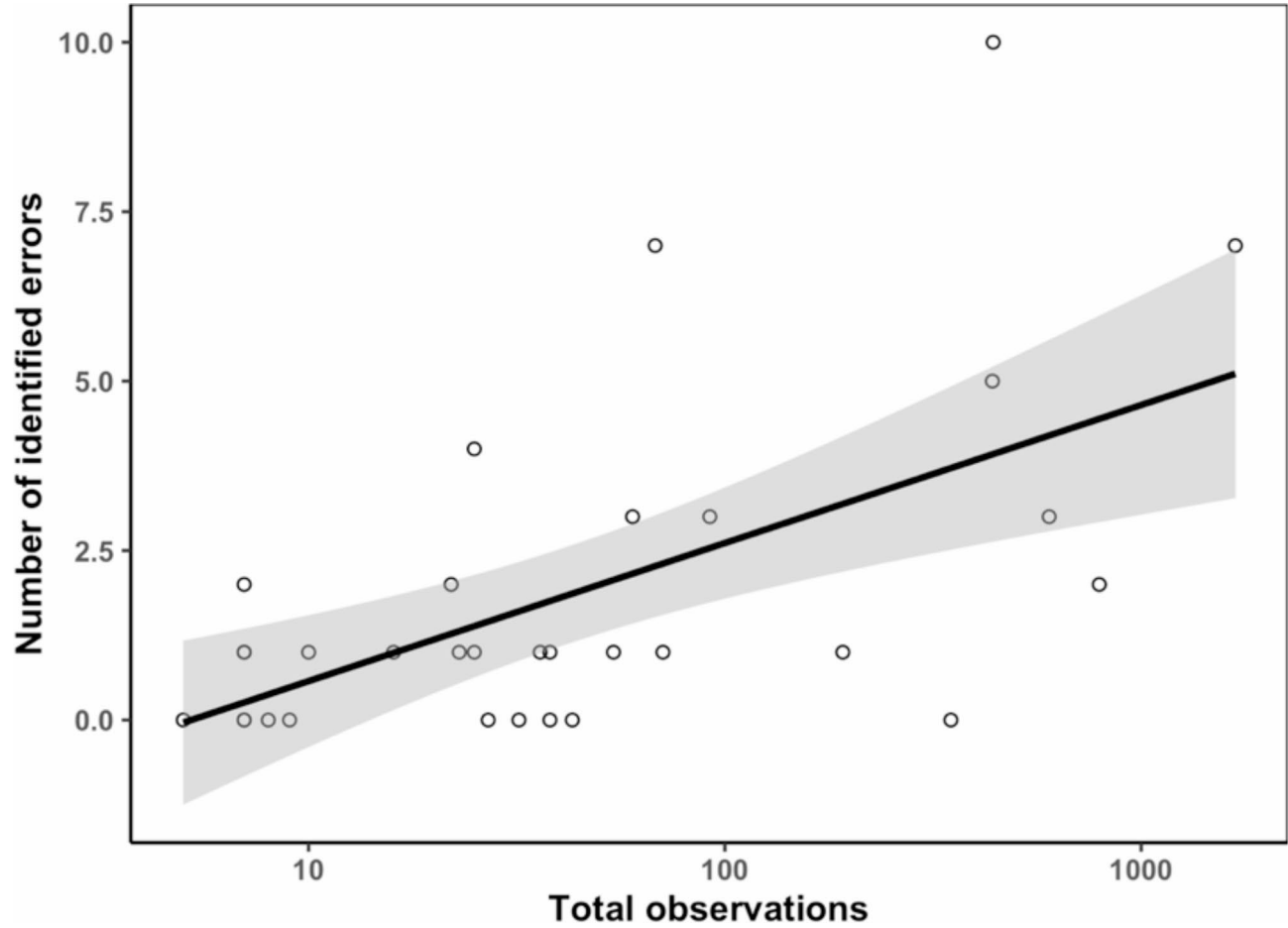


Fig. 1. The number of identified errors per observer was associated with the total number of submitted observations, with a lower error rate in the 50% of observers submitting the highest number of sightings (0.9%) compared to the 50% of observers submitting the lowest number of sightings (5.9%). Dots show raw data, line and standard error (shading) are predicted from a linear model using ggplot⁵² in R.

Variable	Resid. Dev	Resid. df	p
Model 1: data collector			
Feeding	149.57	1, 2666	<0.001
Observer ID	562.83	29, 2666	<0.001
Year	2.31	3, 2666	0.510
Model 2: territory ID			
Year	94.64	3, 2668	<0.001
Feeding	194.76	1, 2668	<0.001
Territory ID	143.06	24, 2668	<0.001

Table 1. Results from binomial general linear models assessing factors influencing certainty in ring reading for models including observer (model 1) and territory ID (model 2). Terms in bold were interpreted as significantly influencing the response variable.

throughout the day until around lunchtime with a peak of just over 60% of visits involving food, then declining gradually throughout the afternoon and evening (Fig. 6b).

Discussion

Our aim was to explore whether data from community scientists can be reliably used to assess wildlife dynamics and demography, providing insights into the utility of equivalent data for a wide range of wildlife species that interact with humans. Specifically, we tested the reliability of identifying individuals through external marks, quantifying demographic parameters during breeding, and estimating the extent of human-animal interactions

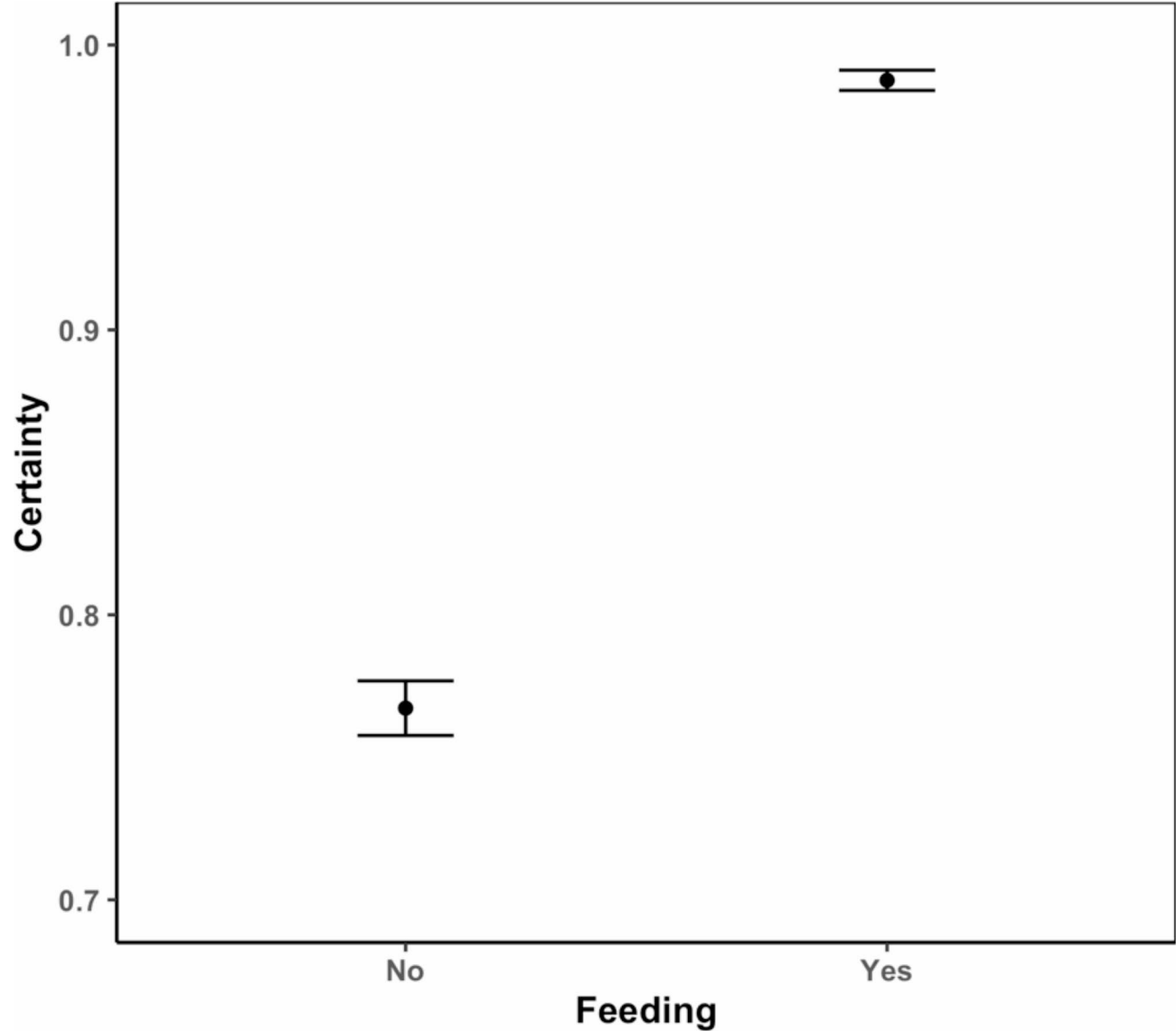


Fig. 2. Observers had higher confidence in a bird’s ring status when they provided food. Dots show mean values; error bars show ± 1 SE.

Variable	Dev	Df	p
Territory	3437.80	11, 1970	<0.001
Hour	304.82	1, 1970	<0.001
Hour^2	305.35	1, 1970	<0.001
Day	32.91	6, 1970	0.921
Report type	4041.40	1, 1970	<0.001

Table 2. Results from a quasibinomial general linear model testing which factors influence the proportion of reports involving supplementary feeding. Terms in bold were interpreted as significantly influencing the response variable.

such as supplementary feeding. We found that the reliability of reading external marks is very high and increased with experience, which is in line with the findings of similar bird ringing studies²⁰. In addition, we found that when community scientists fed the birds, they were more certain of their ability to read their colour ring. Furthermore, we found that community scientist observations were reliable for quantifying family group size, but not for clutch size, given the lack of consensus from multiple observers for any given nesting attempt. Our findings highlight that self-reported data for assessing feeding interactions with wildlife are not comparable

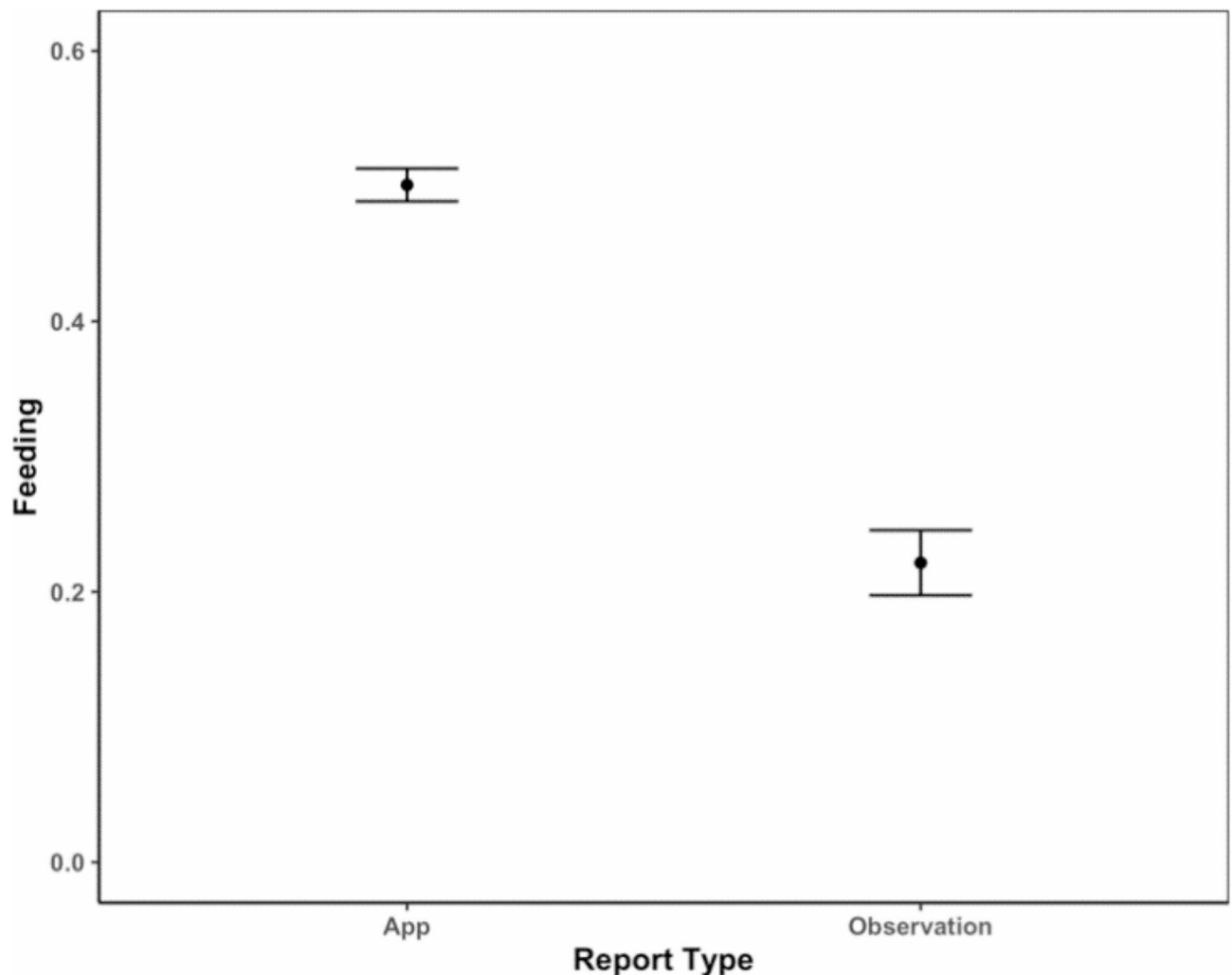


Fig. 3. A higher proportion of App reports ($n = 1693$) involved supplementary feeding than did standardised observations ($n = 298$). Dots show mean values; error bars show ± 1 SE.

with systematic recording methods for our system. Finally, we quantify—for the first time—using standardised behavioural observations, the frequency of interaction of wild mute swans with humans through supplementary feeding and highlight the potential impacts of this common human-wildlife interaction.

Colour ringing projects are widespread methods to assess bird population dynamics and abundance, and such projects often rely on the participation of volunteers reporting their sightings¹⁷. Therefore, it is essential to assess the quality of the data collected if such data are to provide evidence-based solutions for sound species management and conservation strategies¹⁷. Our results showed that ring reading was highly reliable with a 1.14% error rate, which compares favourably to that of other studies where even trained observers misread up to 8% of letters²⁰. Similarly to Kania²⁰, we found that this reliability increased with experience, which we quantified as the number of sightings reported.

Our findings showed that community scientists could not tell whether the bird they were observing was ringed or not for 11.8% of reported swan sightings. By providing the option for community scientists to acknowledge that the ring was not clearly readable but still submit their sightings, this may reduce the likelihood of the submission of “probable” sightings, potentially increasing the accuracy of our dataset. Generally, this metric is not reported in colour ringing projects because only positive identifications tend to be reported. To be viable, a community science project needs to take into consideration that volunteers have a range of skills and equipment (e.g. binoculars) that might affect their resighting certainty, and the accuracy of ring resightings can be affected by the quality of available optics²¹. In addition, species characteristics have an influence on ring reading feasibility. For example, mute swans are often recorded on water, which can make the ring reading difficult (e.g. murky water, legs tucked under the wings). In addition, we assessed the factors that might affect ring reading certainty, and found that certainty in ring reading increased with supplementary feeding. This is probably explained by the birds coming closer to the observer, or changing position in response to the food, increasing the likelihood of the observer being able to read the ring. In other wildlife systems, where individuals may be identifiable using artificial intelligence^{7,8,22}, the collection of a photo alongside additional project-specific

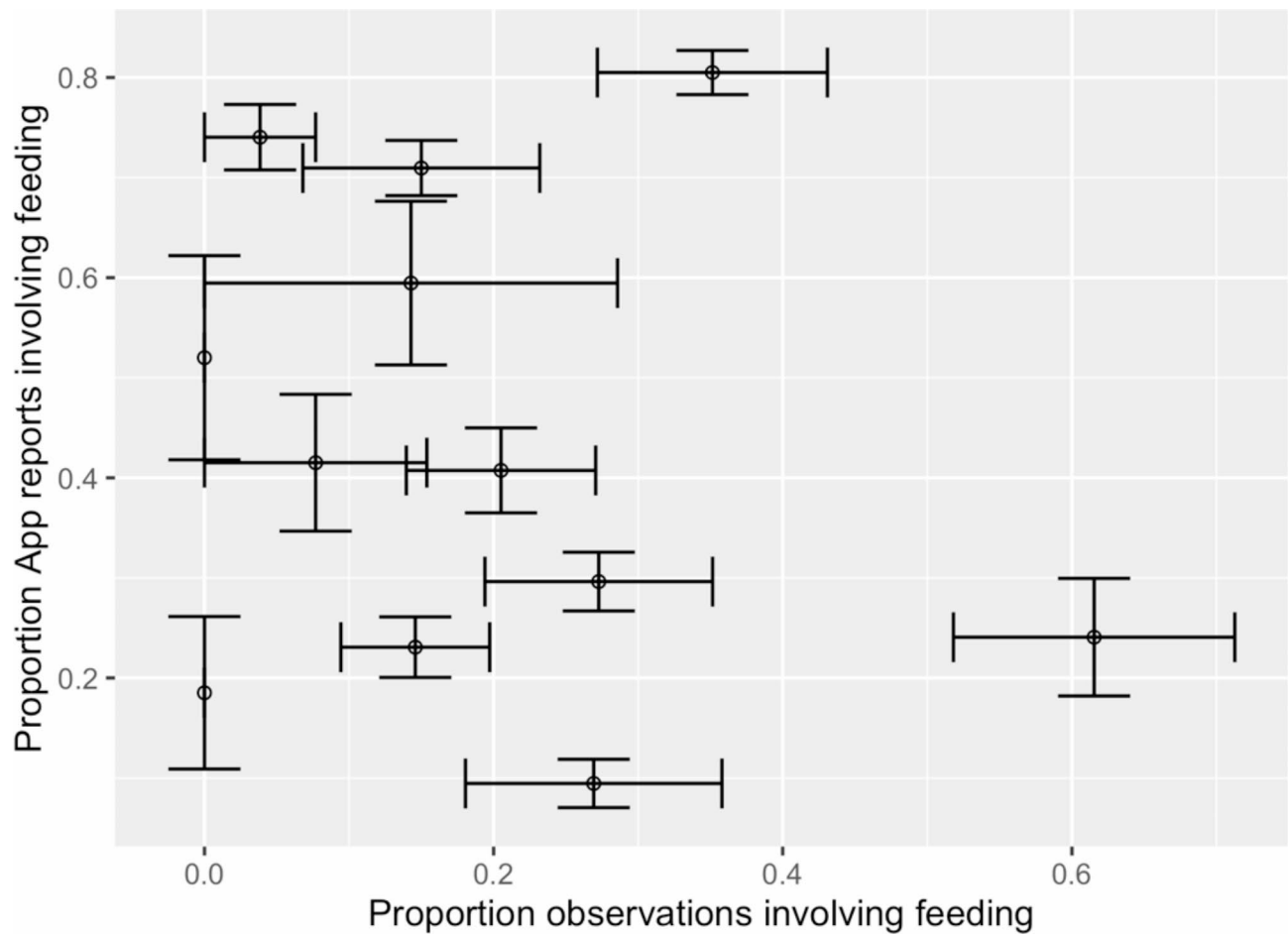


Fig. 4. No relationship was identified between the proportion of app reports and the proportion of standardised observations that involved the feeding of swans at the territory level. Points show mean \pm 1 SE.

Variable	Dev	Df	<i>p</i>
Territory	73.51	17, 303	<0.001
Duration	19.32	1, 287	<0.001
Weekend	0.67	1, 287	0.413
Hour	0.43	1, 287	0.510
Hour^2	0.39	1, 287	0.533

Table 3. Results of a binomial general linear model examining the factors affecting supplementary feeding in the dataset including standardised observations only. Terms in bold were interpreted as significantly influencing the response variable.

data may be more effective at providing individual-level data than reading external markers, such as leg rings. This would potentially negate the individual- or territory-level variation in identification likelihood that we observed.

Community science colour ringing projects usually focus on reporting the location and ring information of each sighting, but additional demographic information such as age, group size or clutch size is rarely recorded. Large-scale projects such as the BTO's Nest Record Scheme (NRS) record such data, but NRS volunteers are generally skilled birdwatchers, and substantial training resources and online support are provided to volunteers²³, which is unlikely to be feasible for most research projects. Our data showed that limited demographic data, such as family size, can be reliably recorded by community scientists, which allows the assessment of reproductive success. However, data on clutch size was extremely varied and generally inaccurate, possibly due to biparental incubation in our system meaning that eggs are rarely visible, and the covering of eggs by adults during laying (pers. obs). The level of demographic information requested from community scientists may also depend on species-specific characteristics; in our system it is relatively straightforward to distinguish pure white adult swans from grey cygnets and juveniles, meaning that the age composition of groups is easy to determine.

Variable	Dev	Df	<i>p</i>
Territory	364.03	24, 1876	<0.001
Duration	123.34	1, 1876	<0.001
Weekend	3.20	1, 1876	0.074
Hour	29.31	1, 1876	<0.001
Hour ²	31.64	1, 1876	<0.001

Table 4. Results of a binomial general linear model examining the factors affecting supplementary feeding including self-reported app data only. Terms in bold were interpreted as significantly influencing the response variable.

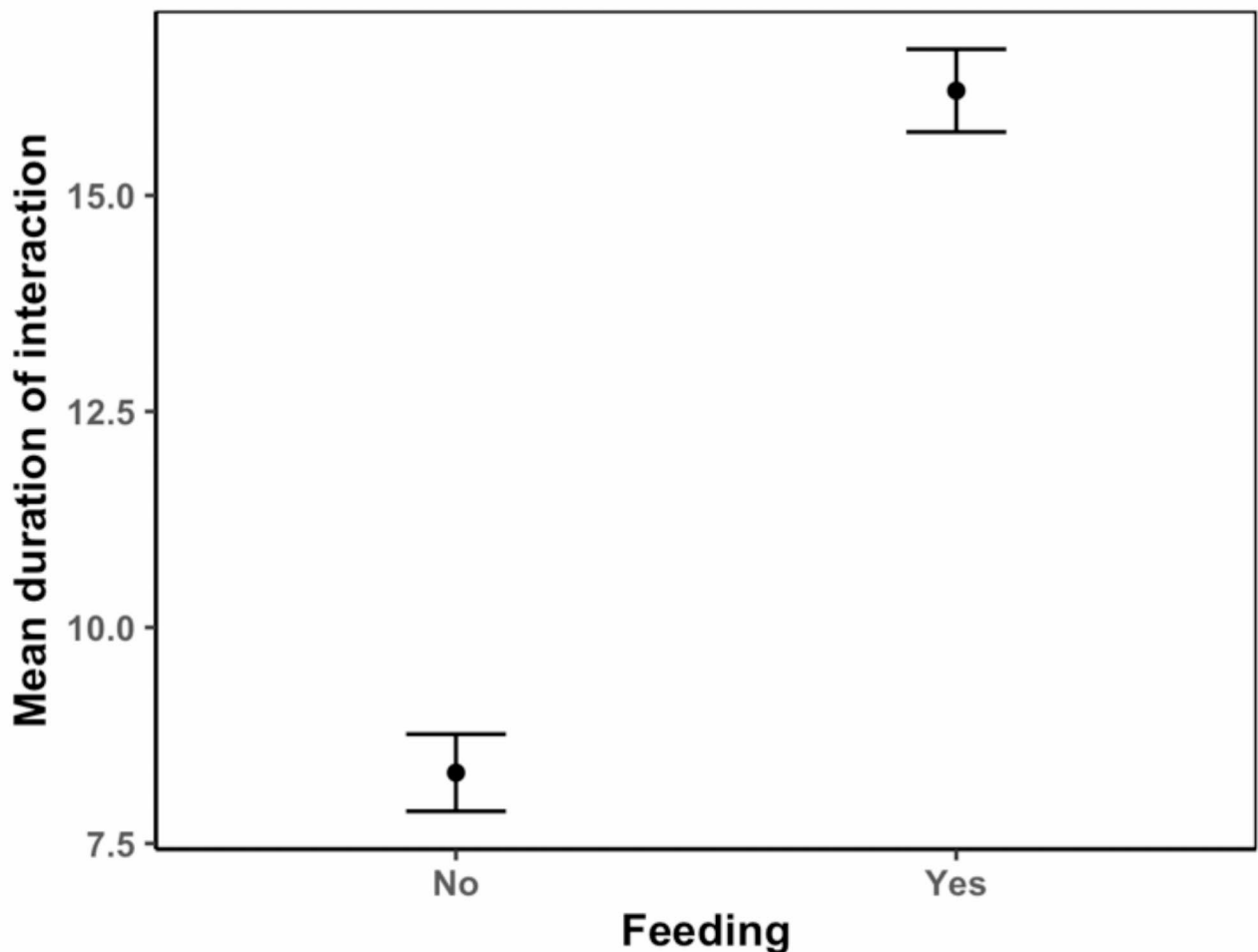


Fig. 5. The mean duration of App-reported interactions (in minutes) was higher when the interaction involved feeding. Dots represent mean values \pm 1 SE.

We tested whether we could use self-reported community scientist data to quantify levels of supplementary feeding, by comparing systematic methods and data collected by community scientists. We found that self-reported data did not accurately quantify supplementary feeding, which is likely based on the biased composition of the data collectors. The nature of our recruitment to the project, and the sightings required, mean that we are more likely to attract data collectors who are already interested in interacting with the swans. Most self-reported feeding occurred in the morning and marginally more often during weekends, whereas the standardised observations do not indicate such patterns, highlighting a temporal difference in feeding interactions between the community science data collectors and observations made by our trained researchers. Furthermore, only five of 23 data collectors never fed the swans, in contrast to one data collector who always fed the swans, overrepresenting supplementary feeding occurrences in our dataset compared to our standardised observations. Therefore, we conclude that systematic observations, although highly time consuming, are at present the most accurate way to quantify supplementary feeding in this particular system and this needs to be taken into

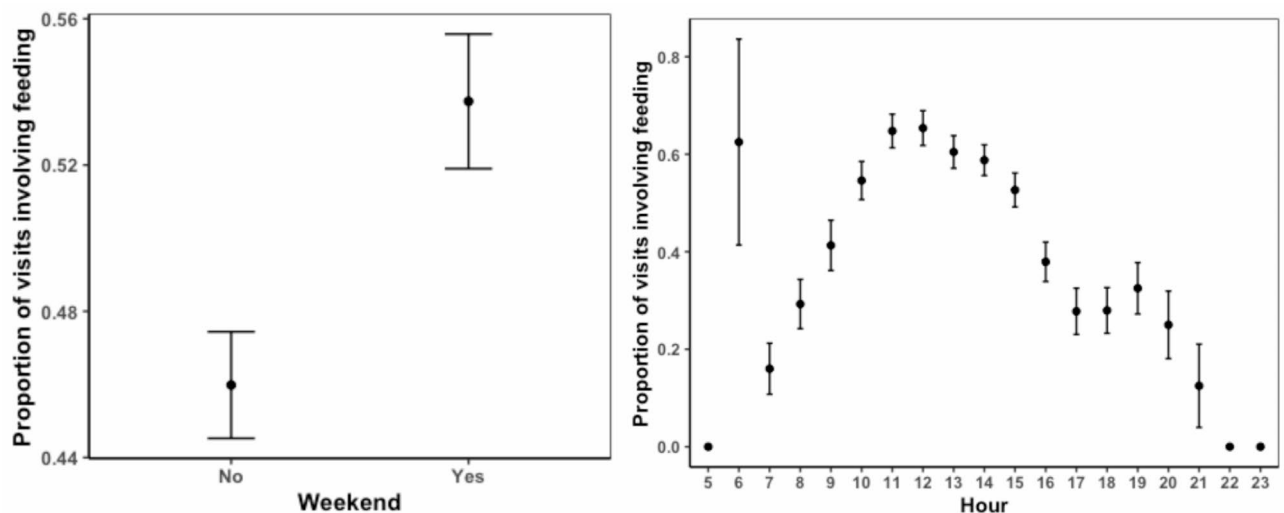


Fig. 6. The proportion of self-reported interactions involving feeding varied (a) marginally between weekends and weekdays and (b) with time of day in a quadratic manner. Dots represent mean values ± 1 SE; for b), Hour is displayed as a categorical variable for ease of visualisation, but is coded as a continuous variable in the statistical model.

consideration when developing strategies to manage supplementary feeding in wildlife. Other methods such as camera traps, or drone observations might prove to be reliable, but these methods also present ethical issues in areas of public access^{53,54} and limitations in terms of designing a sampling strategy to quantify potentially spatially-biased behaviours such as human feeding in a highly mobile species^{55,56}.

Finally, we provide the first quantification of human feeding of waterfowl outside of Australia⁴¹ through standardised behavioural observations, with 22% of observations including swans being fed by humans during observation periods. Given this is such a widespread interaction, it is surprising that the supplementary feeding of waterbirds has not previously been quantified in Europe. We did not identify any strong temporal patterns of feeding events within days or between weekdays and weekends. This highlights the unpredictability of supplementary feeding for waterbirds, for which the implications on their socio-ecology and health are currently unknown. Supplementary feeding can influence every aspect of a bird's ecology⁴⁰, and can be detrimental where the provided food is of lower nutritional quality than that naturally available⁴². However, most research into impacts of supplementary feeding focuses on the provision of a static food source such as a garden bird feeder⁴⁰, or in the context of the conservation of a specific species or population⁵⁷. In contrast, here we have a population where specific individuals are targeted for supplementary feeding, possibly due to proximity of their territory to that of the data collector⁵⁸, or their accessibility to people²⁵. Consequently, more research is needed on the implications of supplementary feeding in this, and other wildlife systems, and further work is needed to estimate how much food (as opposed to how often feeding events occur) is provided to these populations.

Our findings demonstrate that the occurrence and frequency of feeding events differed between territories, and that when people provide supplementary food, this increases the time they spend with the birds. Spending time in nature and interacting with wildlife has been linked to improved mental health for people^{27,28}, with spending longer in nature linked to reduced rates of depression and lower blood pressure⁵⁹. However, wildlife habituation to humans can be detrimental to the wildlife⁶⁰. Swans in particular will often approach people at close proximity, described as 'begging'⁴⁸ which may lead them vulnerable to human interference and injury. In addition, habituation to humans providing food may also reduce anti-predator behaviour⁶¹, which might reduce reactions to their dogs. This may lead to an increase in attacks by domestic dogs: free-roaming dogs in the UK tend to be rare, unlike in other systems where dog attacks on wildlife are of conservation concern^{62,63}. However, in the UK, off-lead dogs being walked by people are common, as are reports of dogs chasing birds⁶⁴, and attacks by dogs are a significant driver of admissions to rescue centres for swans (Yorkshire Swan and Wildlife Rescue Centre, pers. comm.). Therefore, further research is needed to assess how supplementary feeding and associated interactions with humans may impact waterbird welfare.

In conclusion, we found that community science data can be reliably used for colour ringing projects involving large birds, to determine population dynamics (abundance and distribution), and some demographic information such as family size, but not clutch size in our system. Technological advances may mean that such techniques could be applied to a range of different wildlife species, from small birds²² to primates⁸. We also determined that measures of self-reported behaviour cannot be used to accurately quantify human-animal interactions, and that more systematic methods are needed in our study system. However, it may be feasible to collect reliable data in other systems, but this would need to be validated. Finally, this study is the first study to quantify supplementary feeding in swans by the general public. It was found that supplementary feeding is common, but unpredictable, and it increases the duration of interactions between people and swans. Further work to understand the drivers of supplementary feeding, including understanding more about the community

scientists interesting in contributing to such projects and their motivations, would be beneficial. To date, the implications for swan ecology and welfare are unknown; however, considering the findings from previous studies on human-bird interactions in gardens⁴⁰, they are likely to be significant. Given the ecological differences between this system and other systems within which the effects of supplementary feeding are better known, more research is needed to quantify both the occurrence and impacts of targeted supplementary feeding on territorial waterbirds.

Methods

Sites and study system

The study was conducted using an individually marked population of Mute Swans *Cygnus olor* located within 10 km of the centre of the city of Lincoln, UK (53°13'40"N, 000°32'37"W), and the focus of the Lincoln Swan Project. Mute swans are an excellent focal species for community science projects as they are easily visible and identifiable, and generally habituated to humans. Mute swans in the Lincoln population occupy lakes, rivers and canals in the extensive network of waterways around the city (covering ~25 km of linear river/canal, plus associated drains, cut-offs and lakes), and occupy habitats both in the centre of the city and in more rural locations, most of which are accessible via a network of public footpaths, but not easily by motor vehicle.

Mute swans are generally monogamous, and start nesting from March, with 4–7 eggs laid in April–May. Cygnets hatch in May–June, and cygnets tend to remain on their natal territories until late autumn/winter⁶⁵. Following dispersal, juveniles generally join non-breeding flocks, where they remain until they establish their own territories, typically at 4 years of age⁶⁵, although this can be earlier (Lincoln Swan Project, unpubl. data). The Lincoln Swan Project population consists of breeding pairs, juvenile groups and individual birds. Since 2017, annual health checks and captures of birds have maintained the colour ringed population; between September 2017 and June 2023, 281 birds were ringed with both a British Trust for Ornithology (BTO) metal ring, and an individually numbered alphanumeric yellow colour ring, consisting of the letter “L” followed by 3 numbers. The alphanumeric ring was 40 mm high and 40 mm wide, with each digit 20 mm tall and 6 mm wide. Experimental protocols were approved by the University of Lincoln Research Ethics Committee (reference: UoL2020_2236). All methods were carried out in accordance with relevant guidelines and regulations. Our results are reported in line with ARRIVE guidelines where appropriate.

Community scientists and app design

Since May 2020, 90 community scientists have signed up to the Lincoln Swan project to report their swan sightings and get updates from the project. These observers included researchers involved in the project ($n=9$) and well as members of the public ($n=81$) who were recruited through word of mouth and advertisements through the Lincoln Swan Project website, social media campaigns, and the local press. To increase the uptake and inclusivity of the App, anybody aged 18 years old and over could sign up as data collector, and no personal information (e.g. bird watching experience, age, equipment) was requested. To sign up to the project, detailed project information, a consent form and sign-up process was provided via a link to an online survey platform⁶⁶. Once the data collectors had provided their consent to be involved in the project, they were issued with guidelines to record their swan sightings via the Epicollect5 mobile application⁵¹. The Epicollect5 mobile application is a free data-gathering platform, supporting both Android and iOS systems, on which project teams can design their own data questionnaires (for more information and recommendations about the application, see^{51,67}). Swan sightings relied on opportunistic encounters with swans; therefore, no additional instructions were provided to data collectors about potential locations of swans or nests, or how to observe the swans (e.g. using binoculars or not).

For each sighting, the following information was collected via the Lincoln Swan Project Epicollect project (full details are provided in Appendix 1): (1) Data collector passcode (an individual code assigned to the data collector at the time of registration), (2) date, time (both editable in case of retrospective sighting submissions), (3) location (optional GPS positioning of the phone's location at the time of sighting, or a free-text box to describe location or provide a grid reference), (4) whether any swan sighted is ringed (four options: yes, yes but I cannot read it, no, or I do not know), (5) ring number(s) (if known), (6) numbers of juveniles, cygnets and adults, (7) bird on nest (yes or no), (8) if yes at question 7, whether there were eggs or cygnets on the nest, and if yes how many of each, (9) whether and what the data collector has fed the swans, and (10) how long was the data collector's interaction with the swans (Appendix 1).

Standardised behavioural observations

Behavioural observations were recorded on a total of fifteen pairs of territorial adult swans using a standardised protocol of continuous focal sampling methods⁶⁸ by six researchers trained by the project leads (trained researchers; included in the $n=9$ above), from January 2021 to May 2023. This included all regularly breeding pairs of birds within this population that are relatively easily accessible; each pair was targeted for observations on an approximately equal number of occasions (parts of some territories were inaccessible, and birds also sometimes leave their territories to forage on land, meaning not all birds were observed on the same number of occasions). Each observation used the App to record basic data (e.g. observation date, time, location) at the start of each observation period. A total of 317 observations were conducted between 7am and 8pm, and lasted from 5 min to 60 min (mean \pm SD: 29 ± 15.5 min). This variation in length of each observation is mainly due to the swans moving out of sight for over 10 min, at which point, the observation was stopped from the time of the last sighting. For each observation, the date, start and end time of the observation, the ID of the swan pair, their location, and whether supplementary feeding occurred, was recorded. Trained observers were instructed not to feed, approach, or interact with the swans. Supplementary feeding was defined as any food (e.g., bread, seeds) thrown towards the birds when humans were within 10 m proximity. Three pairs either experienced mortality

of one bird during the observation period, or insufficient (<5) sightings of the pair were submitted by data collectors through the App, meaning we could not make comparisons between observation and App data; these pairs were excluded from subsequent analyses.

Statistical analysis

All data from all observers were downloaded from the App at the observation (swan group) level. Where a sighting reported more than one ringed individual, we expanded this into an individual-level database, duplicating this sighting report for each reported ring number and removing any sightings with no associated ring number. Statistical analyses were carried out in R v4.3.1 “Beagle Scouts”⁶⁹.

Analysis 1: reliability of ring sightings, and family group size reports

To quantify the reliability of ring sightings, we used the individual-level database where ring numbers were reported as part of the sighting. We identified errors in ring reports by mapping all sightings of each bird from each year separately. Points were mapped using the bulk entry function of Map Customizer (<https://www.mapcustomizer.com>) and outliers checked manually. If a territorial bird was reported from a different, non-adjacent territory, this was highlighted as a likely reporting error. Often, these errors could be traced back to the transposition of a single digit in the ring. If the accuracy of a sighting could not be verified, e.g. a single report of a juvenile swan was received from a new location, and no photo of the ring was submitted for verification, the record was removed from the analysis because it could not be confirmed. Typographical mistakes in inputting ring numbers, such as rings with too many digits, or ring numbers not yet deployed on birds, were also highlighted as errors. Letter-number transpositions (e.g. replacing the number “0” with the letter “O”) were not considered errors.

To initially test whether our grouping of data from our trained researchers and our data collectors was valid in subsequent analyses, we initially tested for differences in error rates in ring reading between these two groups at the level of the observer. Error rates were non-significantly higher in our trained researcher group ($0.053 \pm 0.020\%$) compared to our data collector group ($0.040 \pm 0.014\%$; GLM, $\text{Dev}2,30 = 0.058$, $p = 0.76$), so we included data from all observers in subsequent analyses. To ensure that the inclusion of data from our trained researchers made no substantive difference to the interpretation of our analyses, we repeated both Analyses 1 and 2 excluding data from our trained researchers (Appendix 2).

To test whether error rate differed among observers, we initially removed data from any observers who submitted fewer than 5 verifiable sightings, to allow convergence of the statistical model. We used a binomial GLM with error status for each sighting (0 = correct, 1 = error) as our response variable, and observer ID as a fixed effect, comparing this with the null model to determine statistical significance.

To test whether the total number of sightings was related to the rate of errors, we assumed a quasi-binomial distribution to account for significant under-dispersion in our data (dispersion parameter 0.06). We specified the proportion of errors identified for each observer as our response variable, and the total number of sightings submitted by each observer as a fixed effect, comparing this model with the null model to determine the statistical significance of sighting number in influencing error rate.

To assess the accuracy of family group size reporting, we restricted data to those collected between April and August (inclusive), before cygnets start to disperse from natal territories. Here, we used group-level sighting data and removed any birds in areas with no nesting attempt, any sightings at territory boundaries (usually of males from adjacent territories) because we could not reliably assign this sighting to a territory/family, and any individuals/groups that can't confidently be assigned to a breeding territory on basis of location or group composition. For each family, we then manually checked the reported number of cygnets and identified errors based on inconsistencies with reports of the same family before and after each sighting. Where inconsistencies in egg or cygnet number were identified, we checked the comments section to determine whether the observer had noted these inconsistencies, or recorded poor visibility of the family (i.e. whether the observation was likely to be correct, or noted as unreliable by the data collector). We only recorded family size errors when the number of cygnets was inconsistent with both previous and subsequent sightings, there were no comments to suggest poor visibility or that the data collector was aware of an inconsistency, and where both adults had been recorded (i.e. the family had not split).

Analysis 2: assessing variation in ring reading

To determine how variation in the certainty of whether the bird was ringed varied with territory and with observer behaviour, we used group-level data from sightings that could confidently be assigned to a breeding territory (as described for Analysis 1). The binomial response variable in a general linear model was designated as Certainty, where the answer to whether the bird was ringed or not was split into either a certain response (1 “Yes” or “No”), or an uncertain response (0: “I don't know” or “Yes, but can't read the number”). Fixed effects were Year (a four-level categorical variable, 2020–2023), whether the observer fed the swans (Yes or No), and observer ID. We tested for effects of territory ID in a separate GLM, due to correlation between observer ID and territory (data collectors tended to visit certain pairs more than others). To assess the importance of each term in the model, we compared the model with and without the term of interest, interpreting terms with $0.05 < p < 0.1$ as marginally significant.

Analysis 3: assessing reliability of quantifying human-swan interactions

To test the reliability of using App-generated data to quantify human-swan interactions, we compared the proportion of visits from the App within which the provision of supplementary food was self-reported, with the proportion of standardised observations within which the provision of supplementary food was observed (i.e. baseline of supplementary feeding for each territory). First, we removed any sightings submitted by trained

researchers from the App dataset, because trained researchers were specifically instructed to not provide supplementary food to the swans. As some data collectors had reported a duration of interaction of 0, we manually changed this to 1 in order to enable us to weight our model taking in to account all sighting reports (below). We created a binomial general linear model in R, with each App report (using the group-level data) or standardised observation as a separate data point. We designated Feeding (a yes or no response to whether supplementary food was provided during each report/observation) as a binomial response variable, with territory ID, time of day (as both linear and quadratic terms), day of the week and report type (App or observation) as fixed effects. To control for the different lengths of time between app visits (where length of interaction was self-reported and varied from 0 to 240 min) and observations (which were standardised as either 30–60 min observations, but ranged from 15 to 60 min due to birds moving out of sight), we weighted our model by length of visit/observation. Where our data were overdispersed, we specified a quasibinomial model.

Finally, to describe patterns in supplementary feeding behaviour from both the App data and observation data separately, we repeated this analysis on each dataset (App and Observation) separately.

Data availability

Datasets are available through Figshare at the following DOIs. Analysis 1 datasets: <https://doi.org/10.6084/m9.figshare.25736781>. Analysis 1 code: <https://doi.org/10.6084/m9.figshare.25736802>. Analysis 2 datasets: <https://doi.org/10.6084/m9.figshare.25736805>. Analysis 2 code: <https://doi.org/10.6084/m9.figshare.25736811>. Analysis 3 datasets: <https://doi.org/10.6084/m9.figshare.25736814>. Analysis 3 code: <https://doi.org/10.6084/m9.figshare.25736817>.

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Author contributions

JD, TR and LM conceived and designed the project. RL, FM, ES, JW and MS conducted standardised behavioural observations. JD and LM conducted statistical analyses and wrote the manuscript. All authors approved the submitted version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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