TECHNOLOGICAL EVOLUTION GENERATES NEW ANSWERS AND NEW WAYS FORWARD: A PROGRESS REPORT FROM THE FIRST DECADE AT THE KARLSÖ AUK LAB

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ABSTRACT

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In 2008, we built an artificial nesting construction for Common Murres *Uria aalge*, the Karlsö Auk Lab, on an island in the Baltic Sea (Hentati-Sundberg et al., 2012). The aim was to create an environment in which the birds could be readily monitored and accessed, and technological equipment easily installed. In this current paper, we report on murre recruitment to the Auk Lab over the first decade, assess the performance of the birds living on the lab compared to natural cliff ledges, and revisit the original research questions. We conclude that the tremendous developments in sensor technology (video surveillance, automated scales, thermal cameras, weather sensors) and artificial intelligence was not anticipated 10 years ago. Several major scientific insights, including the effects of eagle disturbances and heat stress on the murres, have come as surprises and have been driven mainly by the technology's potential to deliver data with a resolution unattainable using traditional field studies. The dramatic increase in data volumes has partly been paired by automated analysis methods, but some aspects of the new technology, notably individual identification, have been more difficult than anticipated. The investment costs for information technology infrastructure, data storage, and processing capacity have also been substantial. We finish the paper by sketching out new research questions that will guide the next decade at the Auk Lab and repeating an invitation for research collaborations beyond our planned research focus.

Key words: automation, artificial intelligence, big data, Common Guillemot, information technology, long-term studies, seabirds

INTRODUCTION

Studies of marine birds have played a significant role in advancing knowledge of animal demography and behavior and the dynamics of the ecosystems they inhabit (Cury et al., 2011). Seabird ecologists have been particularly successful in running long-term studies following groups of known/marked individuals, largely thanks to some of the basic ecological characteristics of seabirds: longevity, colonial breeding, and high levels of philopatry to breeding sites (and to a lesser extent, natal colonies). Several long-term place-based studies, some dating back almost a century, have contributed to unique insights on general breeding and feeding ecology, state-dependent decisions, adaptation, and plasticity (Croxall, 1987; Lecomte et al., 2010; Rebke et al., 2010; Reed et al., 2008; Saraux & Chiaradia, 2022; Sealy, 1990). From an environmental management and conservation perspective, such long-term studies have also been key in understanding and predicting the effects of human drivers on species and ecosystems, including oil spills (Gaston et al., 2013; Votier et al., 2008), bycatch (Michael et al., 2017; Žydelis et al., 2009), fishery depletion of prey (Grémillet et al., 2008), and climate change (Barbraud & Weimerskirch, 2006; Jenouvrier et al., 2005; Thompson & Ollason, 2001). Seabird ecologists have often been progressive in adopting emerging methods and technologies to gain new insights. This includes the use of bio-loggers for tracking movement and activities (Jouventin & Weimerskirch, 1990; Korpela et al., 2020; Strøm et al., 2021; Tremblay et al., 2003; Wilson et al., 2020), pit-tags for automated recording of presence/absence data (Ballard et al., 2001; Becker & Wendeln, 1997), automatic scales to measure body-mass change (Ballard et al., 2010), innovative blood sampling techniques (Becker et al., 2006), and drones for automated habitat mapping and bird counting (Corcoran et al., 2021). Recently, various applications of deep learning and artificial intelligence (AI) have been employed for analyzing logger data, automating population counts, and assessing behavior (Browning et al., 2018; Edney & Wood, 2021; Weinstein et al., 2022).

Technologies such as these can enable major scientific advancements, although deploying them in the seabirds' natural breeding habitat often includes practical challenges. Many species are sensitive to disturbances, and their colonial breeding implies a risk of unintentionally disturbing hundreds of individuals when capturing single birds (Carey, 2009; Carney & Sydeman, 1999). This is particularly true for the Common Murre *Uria aalge* (hereafter, murres), which is one of the most densely breeding of all seabirds (Birkhead, 1978, 2023). Because of the remote and often inaccessible breeding locations, field sites also frequently lack adequate infrastructure such as electricity, network coverage, and shelter, thus limiting the potential to implement new and automated

technologies for field studies. However, the development of solar power–generating technology has alleviated that. Finally, traditional field studies require specialized field staff and are thereby costly to operate.

With these challenges in mind, we built the Karlsö Auk Lab in 2008 and published a paper (Hentati-Sundberg et al., 2012) in which we described the lab's infrastructure and outlined several research questions that would guide our activities. In the present paper, we describe the recruitment of birds to the new structure during its first decade, compare these birds with those on surrounding natural ledges in terms of breeding success and phenology, revisit the original research questions, report on some surprising results and challenges, and outline a new set of research questions for the coming decade of research at the Auk Lab.

MATERIAL AND METHODS

The Karlsö Auk Lab is an artificial construction located in the middle of the seabird colony on the island of Stora Karlsö in the Baltic Sea (57.29°N, 017.96°E). It is a 10-m tall and 5-m wide box constructed as a steel skeleton covered by oak boards with two distinct compartments: an outer section with 35 breeding ledges for murres (capable of hosting at least 300 breeding pairs) and 67 nest boxes for Razorbills *Alca torda*; and an inner compartment for researchers and equipment (Fig. 1; construction described in detail in Hentati-Sundberg et al., 2012). The inner compartment is concealed behind a wall and allows detailed observational studies to be carried out with minimal disturbance to the birds. Online annotated three-dimensional (3-D) models at www.balticseabird.com/auklab can be used to interactively explore the detailed features of the construction.

Over the years, the Auk Lab has been equipped with various sensors to allow for automated high-resolution data collection. We started experimenting with video cameras in 2014 and have concluded that Internet Protocol (IP) camera technology (i.e., cameras connected to a local network with centralized control and recording) is the best solution in terms of price, reliability, and flexibility. Our current system, installed in 2023, includes approximately 60 cameras (Provision ISR; Kfar Sava, Israel) that stream continuously over a local network and are recorded through a Network Video Recorder with 110 terabytes of storage. A smaller but similar version of the system has been described in detail (Hentati-Sundberg et al., 2023a). Cameras are used for a range of specific monitoring purposes. While the majority record the breeding ledges from above, there are also cameras filming sideways to support stereo vision, cameras filming weighing scales for ring reading, and cameras filming inside Razorbill boxes. The benefits of continuous camera monitoring are multiple: (i) rare events are never missed; (ii) less urgent analysis can be conducted after the field season, allowing researchers to prioritize activities that must be done in the field; (iii) infrared light provides full visibility during hours of darkness; (iv) exact data concerning the timing of all events (laying, hatching, fledging) and reasons for all failures are recorded; and (v) future research questions

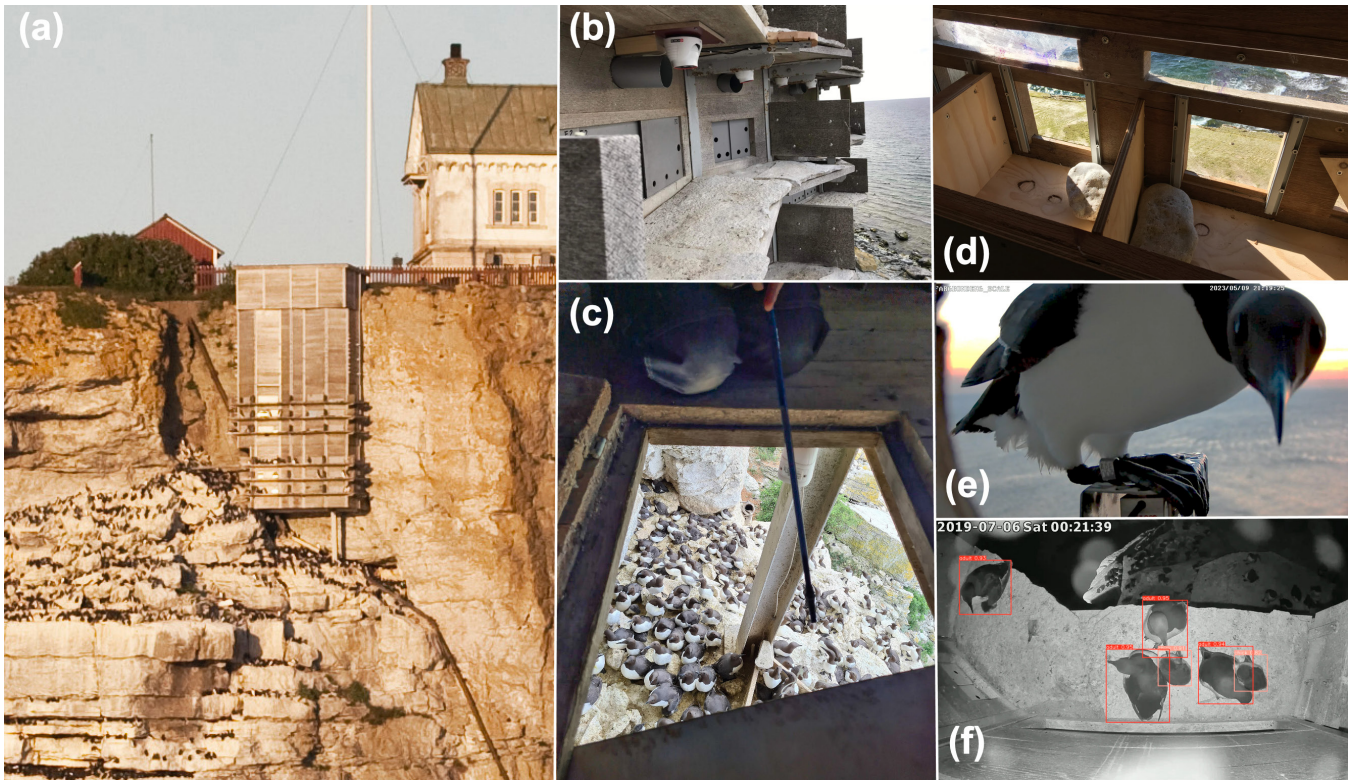

Fig. 1. The Karlsö Auk Lab (Stora Karlsö, Baltic Sea): (a) outside view; (b) Common Murre *Uria aalge* ledges with surveillance cameras and sliding hatches for catching; (c) catching birds breeding on natural ledges beneath the Auk Lab, through one of the floor openings; (d) Razorbill *Alca torda* boxes (with their roofs opened), seen from the inside; (e) Common Murre male ADE009 (hatched at the Auk Lab in 2018 and recorded breeding for the first time in 2023), standing on a weighing platform (https://youtu.be/GB_U9cjYkog); (f) example of closed-circuit television footage for one ledge at night, with an object-detection model identifying adult birds and chicks (https://youtu.be/y4yiNEZIiAU).

can be formulated using recorded material that would otherwise require several additional years of data collection.

In an effort to collect high-resolution biometric data while minimizing bird handling, we also built an automated system for weighing birds, with four scales installed in 2022 and an additional four added in 2023. As murres do not build nests, we have not yet solved the problem of how to construct scales for individual nesting spots. Instead, scales have been constructed as isolated viewpoints at which immature birds and partners that are not currently incubating or brooding can take temporary rests, and all scales have dedicated cameras to identify individuals (Fig. 1e). Continuous data logging at a rate of 10 measurements/second has generated over 5,000 individual weight events over the 2022 and 2023 field seasons—many individuals weighed themselves repeatedly, with some repeat visits over the course of the day. Additional data recorded at the Auk Lab include (i) air temperature, solar radiation, precipitation, humidity, wind speed, and wind direction from a dedicated weather station (Davis Vantage Pro2, David Instruments Corporation; California, USA); (ii) localized ambient temperature at the walls of the Auk Lab, close to the breeding ledges (U0541 datalogger with PT1000 sensors, COMET Systems; Roznov pod Radhostem, Czech Republic); and (iii) thermal properties of birds and their surrounding breeding environment (A100 thermal camera, FLIR Systems, Inc.; Oregon, USA).

The artificial construction was built for the murres and initially named the Murre Lab. However, relatively soon after construction, Razorbills began to colonize and breed on the open ledges meant for murres. In 2019, we installed four nest boxes designed for Razorbills; in 2020, another 63 nest boxes were installed and gradually became occupied (Fig. 1d). Consequently, we changed the name from Karlsö Murre Lab to Karlsö Auk Lab.

RESULTS AND DISCUSSION

Recruitment of auks to the Karlsö Auk Lab

The first Common Murre pair recruited to the Auk Lab in the first spring following construction (2009), and since then, the number of breeding pairs has increased steadily: 103 pairs of murres and 13 pairs of Razorbills bred in the Auk Lab in 2024 (Fig. 2a). Thanks to the intense ringing effort targeting fledging chicks on the beach below the Auk Lab for decades ahead of the construction (45,500 chicks ringed in 2005–2022), 40.3% of the breeding murres at the Auk Lab in 2010–2023 were known individuals (Fig. 2b). Additionally, between 2016 and 2023, 324 chicks were caught through hatches and ringed directly in the Auk Lab. In 2020, we recorded the first occurrence of a murre ringed as a chick in the Auk Lab recruiting as a breeder. By 2023, 32 (17.2%) of the breeding adults had hatched at the Auk Lab in previous seasons (black line in Fig. 2b). This is a much higher fraction than would have happened by chance in this colony of over 20,000 pairs, and this corresponds to earlier findings on the high level of natal philopatry in murres (Sarzo et al., 2019; Steiner & Gaston, 2005).

Among 138 ringed murres of known age that have begun breeding at the Auk Lab, the median age of first recorded breeding was 4 years and the mean was 4.8 years (Fig. 3a). Among these, 11 individuals (8%) began breeding by 3 years of age. Of the total 138 individuals, 81% were observed in the Auk Lab 1–10 years before their first recorded breeding attempt, with the median and mean number of prospecting years being 1 year and 1.6 years, respectively (Fig. 3b). Breeding success clearly increases with age (Fig. 3c) and prior breeding experience (Fig. 3d), with prior experience having a stronger explanatory power than age (weighted R^2 = 0.80 and 0.57, respectively). In the analyses of the effects of age and experience on

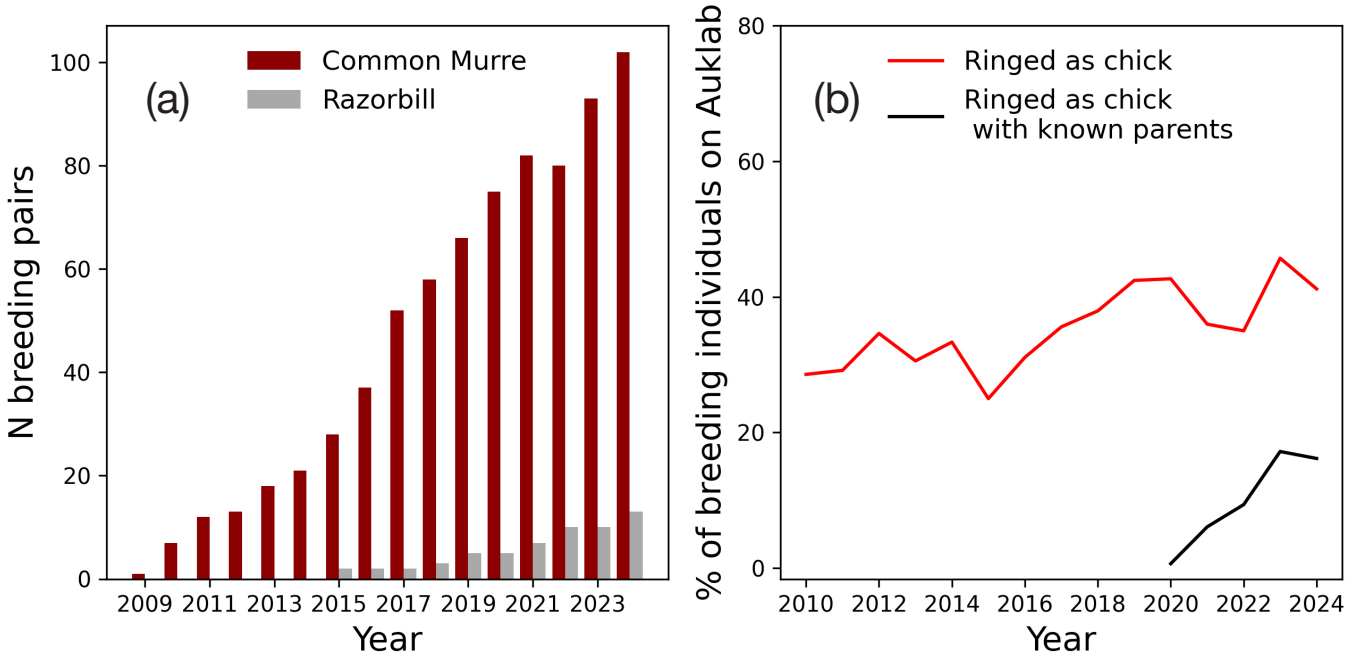

Fig. 2. Recruitment to the Karlsö Auk Lab (Stora Karlsö, Baltic Sea): (a) Number of breeding pairs (red bars = Common Murres *Uria aalge*, grey bars = Razorbills *Alca torda*), and (b) proportion of ringed breeding individuals of Common Murres. Red line = ringed as chicks on the beach below the Auk Lab (unknown parents), black line = ringed as chick directly on the Auk Lab (known parents).

breeding success, we used the age/experience of the youngest and least-experienced individual in the pair, respectively.

Comparison with birds on natural ledges

We conducted a standardized monitoring program to assess breeding success and phenology on adjacent natural ledges beginning in 2005 (see methods outlined in Berglund (2016) and Kadin et al. (2012)). A concern with the gradual transition to studying birds at the Auk Lab was the compatibility of data with those from the natural ledges. To benchmark the artificial ledges against the natural ledges, productivity and phenology were monitored in parallel during 2010–2021. We have found that data from the Auk Lab correspond well to data from natural ledges (Fig. 4). The continuous

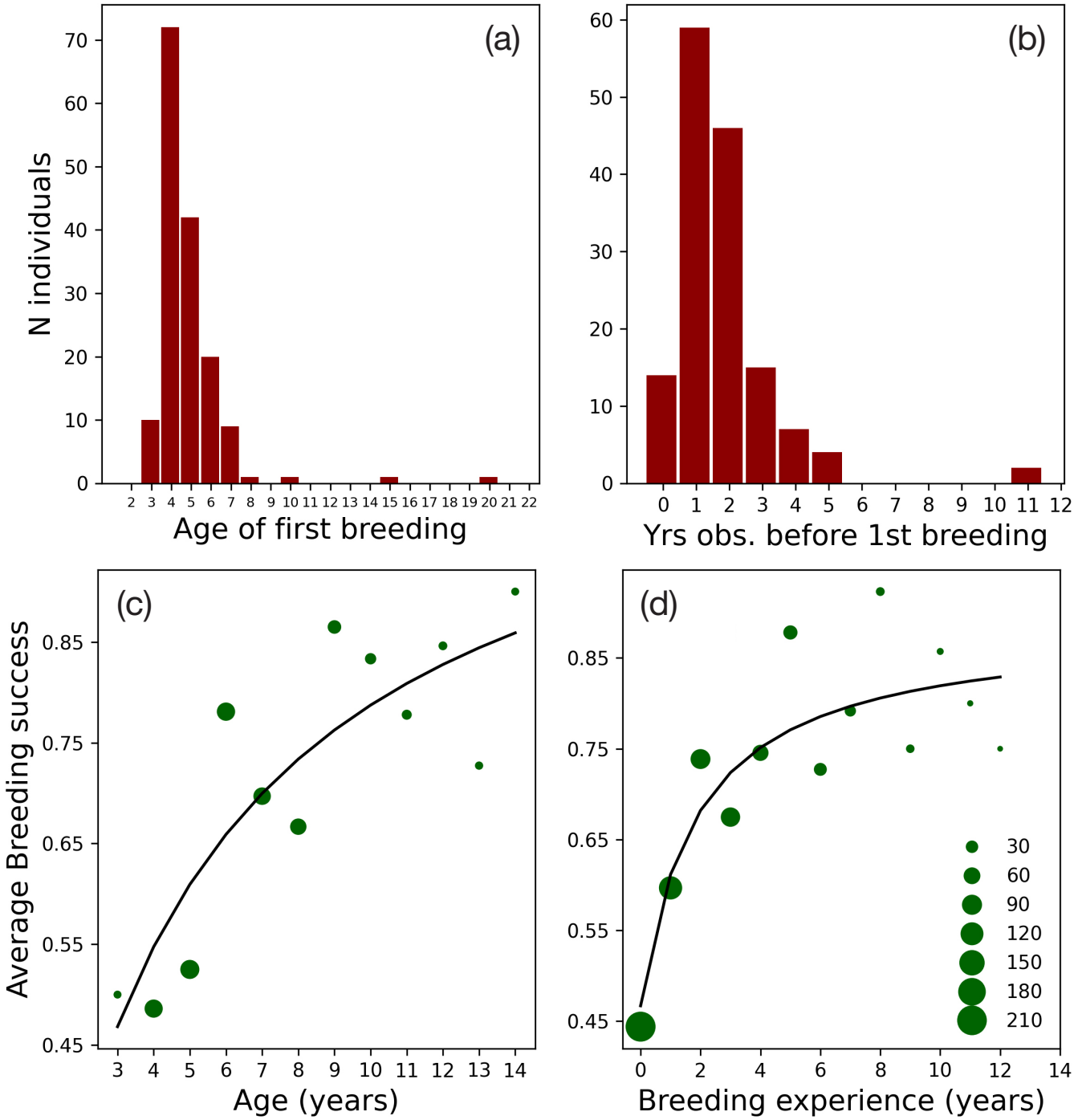

Fig. 3. (a) Age of first recorded breeding in Common Murres *Uria aalge* at the Karlsö Auk Lab (Stora Karlsö, Baltic Sea). The three individuals over nine years of age are probably birds that have bred elsewhere previously and moved to the Auk Lab as adults. (b) The number of prospecting years; 0 means that the first year of observation was also the first year of breeding, including only known-age birds (n = 138). (c) Breeding success as a function of age. (d) Breeding success as a function of prior breeding experience. Sample sizes for panels (c) and (d) are indicated in (d).

delay in breeding onset, the outlier year in 2020, and the high, stable reproductive output were observed both in the Auk Lab and on natural ledges, with little observable difference (Fig. 4).

One benefit of the Auk Lab data is that, through continuous recordings, we can eliminate any uncertainty in the timing estimates of key breeding events. As an example, the minimum time for incubation in 2023 was 31 days, 7 hours, and 17 minutes; the maximum time was 34 days, 5 hours and 11 minutes; and the mean time was 32 days, 19 hours, and 4 minutes (n = 71). The corresponding minimum time for chick-rearing (hatching to fledging) in 2023 was 16 days, 8 hours and 23 minutes; the maximum time was 24 days, 4 hours, and 38 minutes; and the mean time was 19 days, 21 hours and 27 minutes (n = 64).

From the studies of recruitment and breeding performance, we conclude that the low age at first breeding (compared to other locations where murres have been studied; Harris et al., 2016), the high breeding success, and the continuous increase of breeding pairs at the Auk Lab all indicate a population that is doing well in a relatively stable, productive ecosystem. This corroborates previous findings from this colony (Kadin et al., 2012; Olsson & Hentati-Sundberg, 2017; Sarzo et al., 2021).

Original research questions revisited

Our 2012 *Marine Ornithology* paper (Hentati-Sundberg et al., 2012) outlined six questions that we hoped to answer through detailed studies at the Auk Lab. Now, we revisit those questions, reflecting on what has been difficult, interesting, time-consuming, etc. when building up a new field research facility.

Question 1: How does sex and age influence state-dependent responses and trade-offs to environmental change?

Other than building an infrastructure that minimized observer disturbance, this question was the main motivation for building the Auk Lab. Extensive chick ringing was conducted on the beach beneath the construction over 17 years to establish a baseline for a largely known-age population that would be studied throughout their life span. A decade later, we now have a study population with a large proportion of known individuals at the Auk Lab (as of 2023, 50.5% ringed as chicks and 17.2% ringed as chicks with known parents; Fig. 2b). We have also established that, as expected (see Harris et al., 2016 and a multitude of studies on other species), prior experience and age influence breeding performance (Fig. 3). Sex differences in behavior and performance have not yet been studied. However, with

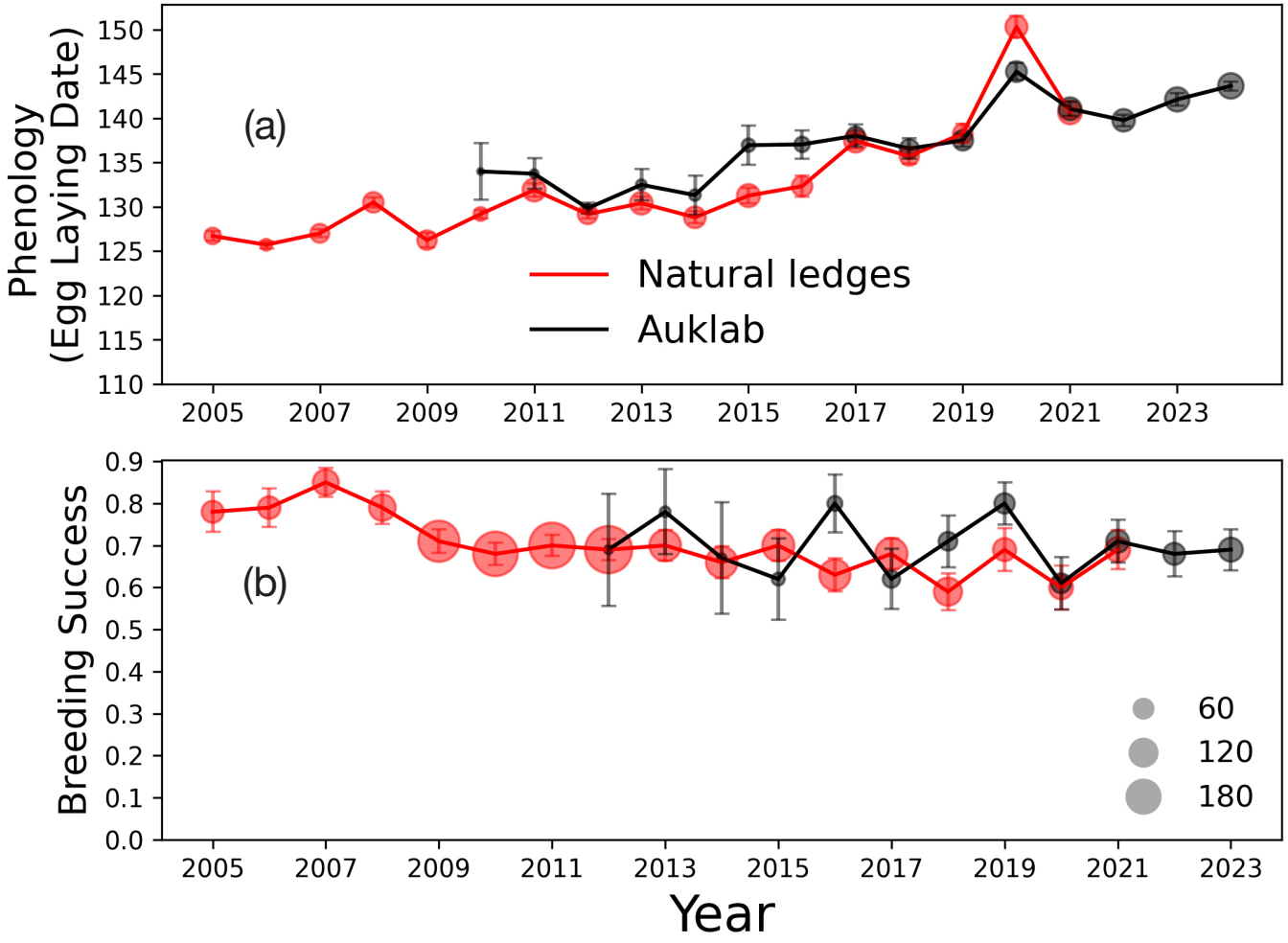

Fig. 4. Phenology (average egg-laying date, (a)) and average breeding success (b) of Common Murres *Uria aalge* on natural ledges (red) and at the Karlso Auk Lab (Stora Karlso, Baltic Sea; black). Standard error is indicated with error bars. The sample size for both panels is indicated in panel (b).

sex confirmed for about half of the 185 known individuals that have bred at Auk Lab (49 males, 46 females) so far, it would be possible to study, for example, sex differences in colony recruitment and first breeding age, the effect of age differences on pair bonds, and other such colony aspects. Likewise, we are getting close to the point where it is feasible to study how responses to environmental change are state-dependent. Following the recent findings on the effects of heat waves (see below), a potential future study could be whether sex/age/experience affects the probability that a parent leaves their chick alone on the ledge when exposed to heat stress.

Question 2: Where, when, and how does seabird foraging interact with fishing?

Intense fishing for European sprat *Sprattus sprattus* and Atlantic herring *Clupea harengus* in the study area prompted questions regarding the interactions between seabirds, fish, and fisheries in the Baltic Sea. Catching murres without significant disturbance was one of the planned features of the Auk Lab, so that birds could be equipped with loggers to record movement and diving behavior. While catching adult birds on the artificial ledges through the sliding hatches can cause significant disturbance to neighboring birds, catching birds through openings in the floor from inside Auk Lab works well (Fig. 1c). Data from loggers have been used to describe general foraging and logger effects on bird performance (Evans et al., 2013, 2020). In parallel, we have performed initial studies of the colony's prey base (Hentati-Sundberg et al., 2018), and we have also used the combined seabird and prey data to calculate prey requirements. The latter have been used to assess the effectiveness of existing fisheries management targets (Hentati-Sundberg et al., 2021b). In addition, fish intended as chick food that had been dropped by adults were collected from the Auk Lab ledges for morphometric analysis to characterize the exact species composition, size, and age of prey, and this method seems to detect inter-seasonal variation in prey availability (P.-A. Berglund unpubl. data, 2012–2024). Fisheries-seabird interactions remain a key question that we have been particularly active in pursuing in recent years. This required investing in an uncrewed surface vessel for continuous fish monitoring in the foraging area of Common Murres and Razorbills around the colony (Carlsen et al., 2024).

Question 3: How can we better understand sperm competition, extra-pair copulation, paternity, pair switching, and mate choice?

We thought this set of questions would benefit from the improved observation facilities compared to traditional fieldwork setups. However, it was not until 2019 that we installed an effective surveillance system that would facilitate such high-resolution studies. Moreover, other scientific priorities delayed the focus on detailed behavioral studies. Our priority in recent years was the development of automated monitoring systems aided by computer vision algorithms (Edney & Wood 2021; Hentati-Sundberg et al., 2023a). A key challenge that remains is the development of automated methods for identifying individuals. Further methodological development within multi-target tracking and automated behavioral analysis (Couzin & Heins, 2023; Walter & Couzin, 2021) could increase the potential for new studies in this realm.

Question 4: How do hormonal responses develop during the breeding cycle?

Originally, we thought that this question would be interesting to study, especially in relation to stress caused by food shortages within and between years. While scientifically intriguing, we have not prioritized this research, partly because of the risk of disturbance due to repeated sampling. We have instead prioritized studies that involve minimal disturbance, such as detailed and automated non-invasive observation studies. However, improved technologies to extract, for example, stress hormones from feathers (Romero & Fairhurst, 2016), allows for the sampling of small pieces of feathers from inside Auk Lab, even without catching birds. This may offer a minimally invasive technique for obtaining qualitative long-term data of known individuals.

Question 5: What is the state of bioaccumulation (fish–bird) and bioelimination (parent–chick) of environmental contaminants in the studied populations?

Like Question 4, this research has not been prioritized, largely due to the risk of disturbance associated with sampling. Again, future technological and methodological progress may eventually re-open possibilities (Adeogun et al., 2022; Schilling et al., 2022).

Question 6: How can ecological engineering contribute to seabird management?

Deciding to build the Auk Lab involved a great risk and effort (money, time, scientific focus) with no guarantee that any birds would find it an attractive breeding spot, although a number of inspiring examples already existed at the time (Becker & Wendeln, 1997; Gill & Hatch, 2002). However, one pair bred during the first season (2009), leading to a subsequent steady increase in numbers. Construction took place at a flat cliff side where there were no breeding ledges. The continuous recruitment has likely benefited from the general population increase on the island, with an average annual population growth rate of 6.2% from 1988 onwards (Hentati-Sundberg & Olsson, 2016). In recent years, we have been contacted by several renewable energy companies that have been inspired by the Karlsö Auk Lab methodology to construct artificial breeding sites as compensation for negative side effects following offshore wind power establishments. Without having any specific opinion on such projects, the Auk Lab and its increasingly automated monitoring technologies could augment the scientific value of such projects, which are becoming increasingly common (e.g., Turns, 2023).

Ecological surprises

Despite well-founded scientific inquiry, ecological field research will always have elements of surprise, and the implementation of new technologies drives the potential for new insights. In our case, the higher resolution achieved by continuous video has helped reveal previously overlooked behaviors and rare events.

Throughout the years, we have been particularly interested in drivers behind breeding success, partly because we initially wanted to establish links between prey abundance and breeding performance, a key focus for seabird studies globally (Cury et al., 2011; Österblom et al., 2008; Warzybok et al., 2018). Since 2019, continuous video footage has enabled us to study the exact sequence of events that have led to breeding failures at the Auk Lab. A surprising proportion of failures are caused by accidents, such as eggs or chicks being kicked down during fights or through plain clumsiness (Table 1). In contrast, despite our previous studies linking chick body mass and breeding performance to prey quality and quantity (Kadin et al., 2012; Österblom et al., 2006), we have

TABLE 1
Breeding success and causes of failures for Common Murres *Uria aalge* continuously filmed at the Karlsö Auk Lab (Stora Karlsö, Baltic Sea)

Year	*N* cameras	*N* filmed breeding attempts	*N* successful	*N* failed	Reasons for failures						
					Abandoned	Clumsiness	Researcher disturbance	Fight	Heat	Predation	Dead when hatched
2022	33	86	54 (63%)	32	5 (6%)	5 (6%)	4 (5%)	7 (8%)	8 (9%)	2 (2%)	1 (1%)
2023	34	93	64 (69%)	29	8 (9%)	8 (9%)	1 (1%)	9 (10%)		3 (3%)	

found no indications of breeding failures linked to food shortages or poor growth of chicks, as is common in some colonies (e.g., Ashbrook et al., 2010).

We have, however, observed a previously unknown driver for breeding failures in the study colony. By combining the video footage with continuous weather data, we have been able to link temperature and sun exposure to thermoregulatory behaviors (i.e., panting, postural adjustments), nest attendance, and even breeding failures (Olin et al., 2024; Fig. 5a). While several studies have linked heat waves to both adult and chick mortality (e.g., Holt & Boersma, 2022; Quintana et al., 2022; Salzman, 1982), the video footage documented the full process leading to the breeding failures and conclusively linked it directly to heat exposure (Oswald & Arnold, 2012). The reduced nest attendance observed at high temperatures based on manual observations was replicated when pairing the temperature data with attendance based on a deep learning–based object detection model (Hentati-Sundberg et al., 2023a).

Another surprising insight came with the COVID-19 lockdown during the 2020 breeding season. Alone on an island that is typically visited daily by large groups of tourists, we noticed that the murres were delaying their breeding and acting unusually nervous. By performing detailed analysis of the video recordings before and during the lockdown (and subsequently when visiting restrictions were lifted), we established that increased disturbances from White-tailed Eagles *Haliaeetus albicilla* were a surprising outcome of the lockdown (Fig. 5b). A sevenfold increase in the presence of eagles had delayed average murre egg laying by about 10 days, and frequent disturbances led to the worst murre breeding season yet recorded in this colony (Hentati-Sundberg et al., 2021a). Following the return of tourists in 2021, breeding success returned to pre-pandemic levels, suggesting that tourists can be used as a strategic measure for mediating predation effects in affected seabird colonies (see also Hentati-Sundberg et al., 2023b; Hipfner et al., 2012).

Technological frontiers and the potential for automation

The Karlsö Auk Lab was initiated as an experiment to explore whether Common Murres would recruit to artificial ledges and thereby contribute to new data that would be difficult or impossible to obtain with standard field protocols. Now, over a decade into the project, we can reflect not only on what has worked and what has not, but also draw some general conclusions about the evolution of field research methods and the value of new technologies for new discoveries.

One thing that we did not expect a decade ago was the remarkable development in the field of machine learning, and especially deep learning within computer vision (Edney & Wood, 2021; Oliver et al., 2023; Weinstein, 2018). New techniques emerging through this general development, driven largely by applications outside the field of ecology, have made the automation of feature extraction a focus of the project. This involves the development of new automated metrics from raw video data that captures essential characteristics of the birds' features and behavior, and includes visual growth estimation of chicks (Hentati-Sundberg et al., 2023a), target tracking of individual birds on the ledge (Hanes & Kad, 2022), automated ring reading using object detection and deep learning–based optical character recognition (Fig. 6a), 3-D pose estimation (Hägerlind, 2024; Fig. 6b), automated identification of prey deliveries using object detection and target tracking (Fig. 6c), quantification of heat stress (Fig. 6d), and automated behavioral analysis. Common for all these examples is that automated feature extraction will generate datasets of a size and resolution that are unrealistic to obtain without machine learning and automation. We believe that AI has the potential to be a valuable ally for any seabird ecologist aiming to streamline analysis and find patterns, and thereby generate substantial insight. However, in the development phase, substantial effort and new competencies in the research and field work teams are required for annotating data as well as building, testing, and deploying models. Annotating video frames for multiple objects (such as multiple birds) takes at least one second per object for a square-shaped bounding box and at least 30 seconds for a segmentation mask; typically hundreds to thousands of annotations are needed to train a well-performing AI model. To put this into context, however, with our camera system producing *ca*. 7.8 billion image frames in 2023, it would take a human analyst 247 years to go through the material at a rate of one frame per second. This triggers our first questions for the next decade:

- Can all types of behavioral and performance data normally collected in seabird observational studies be fully automated?
- How do we best bridge the knowledge gap between seabird ecologists, engineers, and computer scientists? Do seabird ecologists need to become engineers and vice versa, or can we build networks and systems for better long-term collaborations?

- Can systems building on real-time inference and iterative short-term forecasting (e.g., Dietze et al., 2018) speed up the process of increasing our knowledge of seabirds and their relation to the marine environment, and thereby contribute to better management of ocean resources?

Potential for new insights with known individuals and high-resolution data

We now have a breeding population at the Auk Lab in which the identity of the majority birds has been known since they hatched. The ongoing automation also means that we increasingly receive data on the performance of these known individuals on a daily and hourly basis (even down to the minute and second), all without their awareness of our existence. Now, more than ever before, we can properly monitor this entire sub-colony. With automation of behavioral analysis and individuals with known genetic relationships, we are getting closer to studying biological phenomena that have previously been limited to controlled experiments in lab settings, such as the emergence of individuality and inter-generational evolution of strategies and behavior (Freund et al., 2013; Kempermann et al., 2022).

One of the key opportunities here is to look not only at the state of the individual (sex, age, prior experience, etc.) but also how individual variation in strategies, and even personality, affects performance. Anecdotally, through studying long-term video material, there appears to be distinct patterns in social/anti-social behavior between individuals. However, time constraints have limited the progress in pursuing these observations. Exploring how individual-specific behaviors such as these are influenced by changes in the environment (temperature, feeding conditions, egg-site density, etc.) adds further relevance and complexity to this topic. Heritability is another intriguing concept, where several aspects can increasingly be studied across generations. This leads to another set of emerging research questions:

- How do responses to environmental fluctuations vary between individuals?

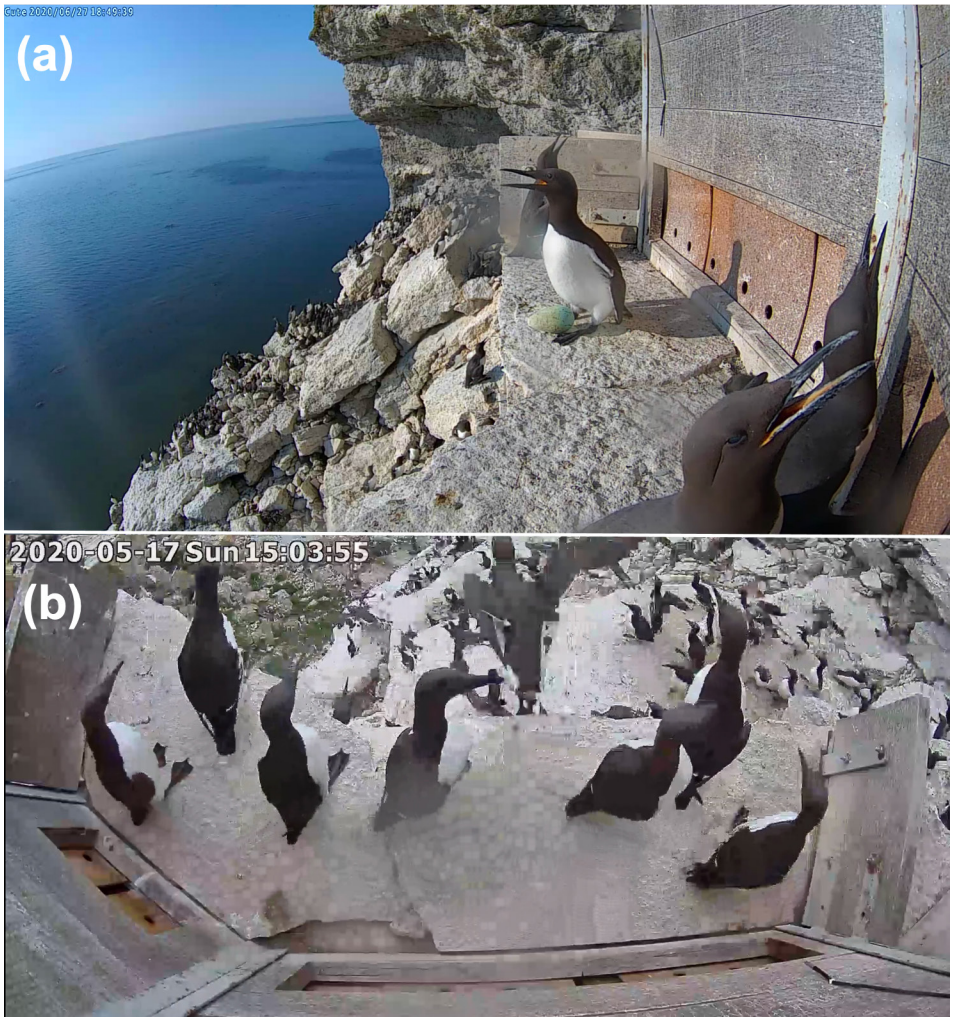

Fig. 5. Images from video footage of Common Murres *Uria aalge* at the Karlsö Auk Lab (Stora Karlsö, Baltic Sea). (a) Three adults are shown exhibiting behaviors relating to heat stress, i.e., panting and orientation towards the sun (see also Olin et al., 2024). The bird in the middle of the frame lost its egg a couple of minutes later (https://youtu.be/iv3Yhy8guFY). (b) Example of disturbance from a passing by White-tailed Eagle *Haliaeetus albicilla* (eagle not visible in the image/video). Such disturbances were particularly frequent during the COVID-19 lockdown in 2020 (https://youtu.be/oE6Sg_zYH9w).

- How do individual strategies develop, and which aspects are important when forming and maintaining pairs?

- How does individuality transfer over generation bonds?

Understanding the link between seabirds and the marine environment

Studying seabirds in detail at their breeding site inevitably misses a crucial aspect of their life cycle: their at-sea activities, both during and outside the breeding season. The truly impressive development of biologging equipment during the last few decades has led to many important discoveries (e.g., Edwards et al., 2013; Patterson et al., 2022; Thiebault et al., 2014; Wakefield et al., 2013). However, we are also aware of the limitations of biologging in terms of limited sample sizes, relatively high costs, disturbance due to attaching equipment and catching birds, and difficulty in capturing group and community dynamics (Bodey et al., 2018; Evans et al., 2019; Sequeira et al., 2019). Another challenge for seabird studies is the relatively limited understanding of prey abundance and distribution. Here, new autonomous technologies (De Robertis et al., 2019; Swart et al., 2016) can pave the way for new types of high-resolution studies with the potential to close the gap between observed foraging behavior and prey distribution/response (Carlsen et al., 2024).

This leads to our last set of questions for the coming decade:

- Can alternative non-intrusive methods be developed for continuous and high-resolution studies of seabird distribution at sea?

- Can we strengthen the mechanistic understanding of the link between seabirds and their prey through autonomous and automated data-collection methods?

- Can seabirds indicate prey supplies at a detailed scale (day/hour) and thereby inform short-term management interventions for sustainable fisheries?

Challenges

While many research opportunities have arisen through the Auk Lab, not all studies have been successful, and some aspects have been more difficult than we initially anticipated. Automating the identification of birds in order to assess individual breeding performance is one such remaining difficulty. From the video recordings, we can generally assign an observed individual to a pair, and in some cases, we can see the ring and thereby link it to an individual. However, automating this requires both robust individual identification as well as tracking the individual across thousands

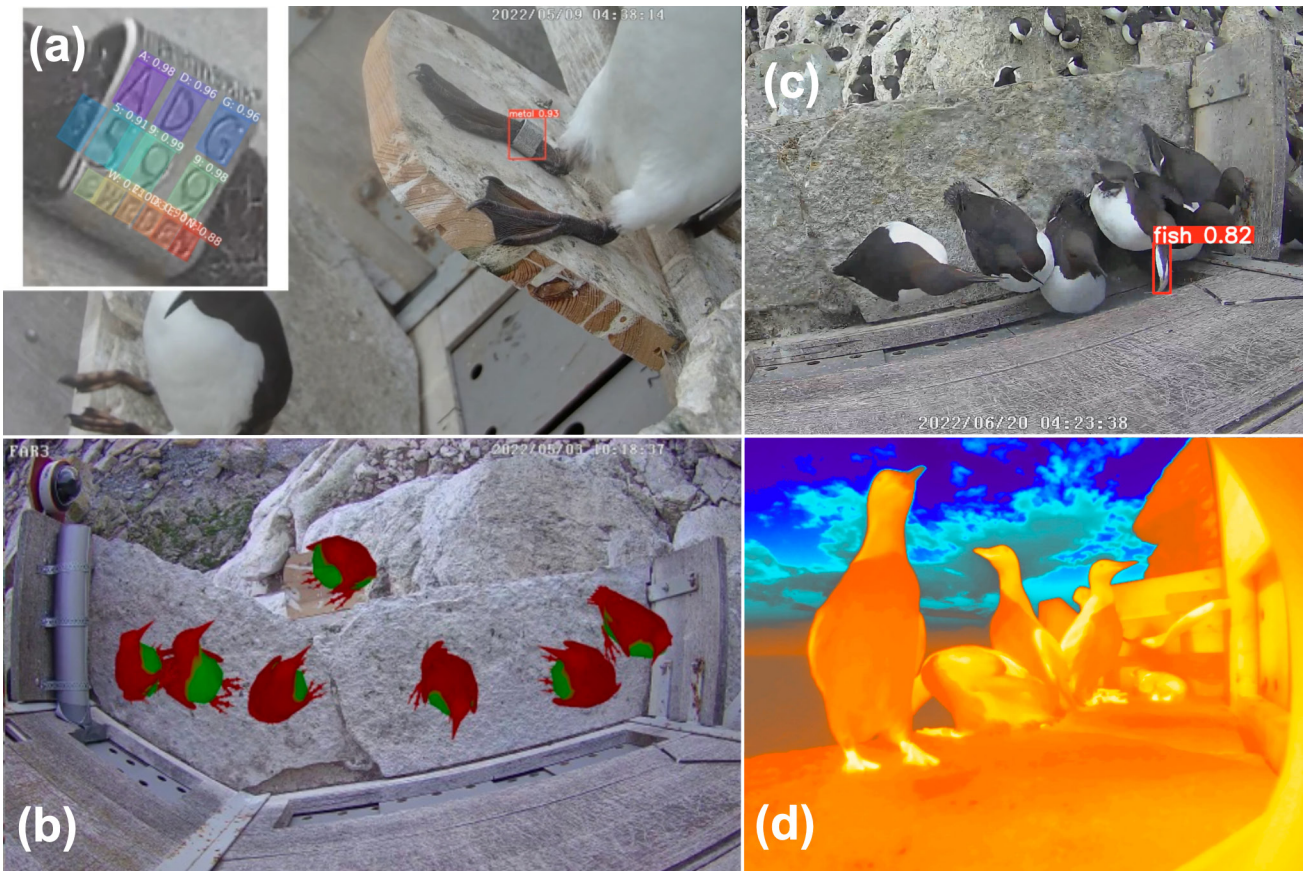

Fig. 6. Examples indicating ongoing development of new sensor and artificial intelligence applications at the Karlsö Auk Lab (Stora Karlsö, Baltic Sea): (a) automated reading of bird rings (https://youtu.be/R9F8pi3oIPQ), (b) pose estimation to infer behaviors, (c) automated identification of fish deliveries (https://youtu.be/jvjtsskmQn4), (d) quantification of heat stress using a thermal camera.

of video frames. Multi-object tracking is a classic challenge in computer vision, and many trackers use object features (e.g., color of clothes, individual patterns) for obtaining robust tracks (Hanes & Kad, 2022; Luo et al., 2021). Common Murre individuals appear very similar, which poses a serious challenge. Ongoing work with identification based on ring readings (Fig. 6a) and new multi-object trackers could potentially solve this problem.

The financial costs of investing first in the general infrastructure (*ca*. €450,000 in 2008 prices) and then in various sensor systems, storage, network, and computing, has been substantial. The costs over the past five years (2019–2023) in equipment has been approximately €31,000 for sensors, €16,000 for general information technology infrastructure, €11,000 for data storage and backup, and €9,500 for computational resources. In addition, there is a significant staffing cost for both building the systems in the field and developing algorithms for analyzing data. Whether these investments are worthwhile will depend on the scientific output in the years to come.

CONCLUSIONS

While technological development within research is very much driven by the questions asked, we also note that this can act in the opposite direction: new techniques also generate new research questions. Thus, we think that the new types and volumes of data generated with these techniques can help stimulate curiosity-driven research, where observations not easily obtained with traditional field techniques (e.g., behaviors during the night) can open new avenues for scientific inquiry. As our own expertise and imagination place further boundaries on the questions pursued, we would like to repeat the invitation extended at the outset of the project (Hentati-Sundberg et al., 2012) for new collaborations and innovative ideas. Much of the project's progress so far was made possible only because of collaborations with other biologists and computer scientists, and we expect this to continue.

Finally, while we see the great potential of technological innovation and novel lines of research, we also recognize the crucial importance of consistent, long-term monitoring of key parameters such as phenology, breeding success, colony size, nest attendance, and chick-feeding frequencies, regardless of the method of data collection. Time-series data like these, to which seabird scientists world-wide have made an enormous contribution over the past decades, are vital for understanding how our ecosystems are responding to ongoing environmental change. Our study of seabirds at Stora Karlsö, lacking support by any official monitoring program, has likely made us more flexible in our approach, allowing us to experiment with methods and techniques, rather than being tied to a specific sampling regime. Additionally, the small but persistent (since 1997), and rather unrestricted, funding from World Wide Fund Sweden has promoted innovation.

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AUTHOR CONTRIBUTIONS

JHS: Conceptualization, formal analysis, funding acquisition, visualization, original draft preparation, review, editing. PAB: Data curation, methodology, review, editing, investigation. ABO: Formal analysis, review, editing. AH: Investigation. HÖ: Conceptualization, review, editing. AAC: Investigation, review, editing. QQ: Review, editing. OO: Conceptualization, funding acquisition, review, editing.

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