Counting birds and other hard problems

Monitoring bird populations through volunteer-collected observations

Birds
Science
People

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British Trust for Ornithology @_BTO

The British Trust for Ornithology

Birds Science People

- We are an independent charitable research institute
- We monitor UK birds with the help of over 40,000 volunteers
- We employ c. 120 staff
    - c. 50% scientists
    - c. 50% communicators, fundraisers, volunteer coordinators, administrators, software/database/web developers

- We don’t advocate but aim to:
    - informing solutions to enhance bird populations through monitoring and research
    - inspire, engage and empower a diversity of people to discover and value nature.

Image: DAVID TIPLING

Why monitor (bird) populations?

- Monitoring is essential for
  - identifying the species and sites of greatest concern
  - assessing progress in conservation efforts
  - evaluating the impact of policies and actions
- Birds are useful biodiversity indicators
  - responsive to environmental change
  - widespread
  - generally conspicuous
  - comparatively well-studied

BTO data collection schemes

- Demographic Monitoring
    - Ringing Schemes
    - Nest Records Scheme
- Population Monitoring
    - Breeding Bird Survey
    - Wetland Birds Survey
    - Garden Birdwatch
    - Bird Track
- Movement and Migration Monitoring
    - Species-specific ringing and tagging projects
- Other Surveys
    - Atlases (comprehensive distribution mapping in ~20 year cycles)
    - Species-specific surveys (e.g. Woodcock Survey in 2023)
    - Bespoke surveys/survey designs for industry and government
    - Acoustic surveys for bats and birds
    - …

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  - **Ringing Schemes**
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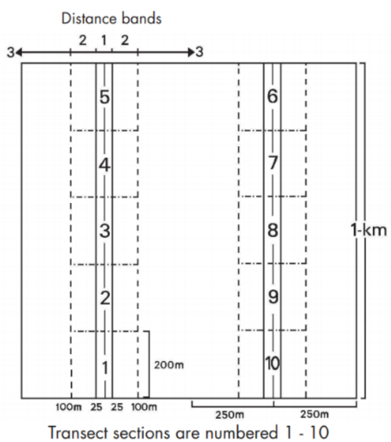
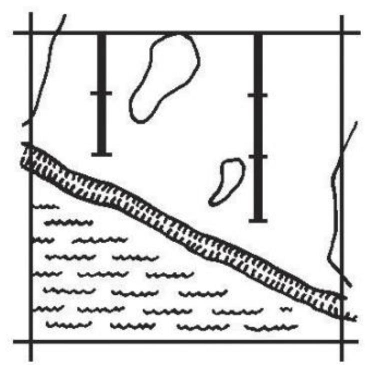
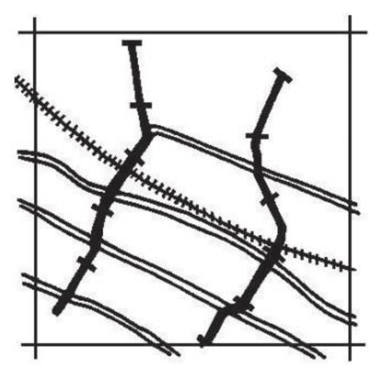
How do we count UK breeding birds?

- Breeding Bird Survey (BBS) 1994 - present
  - strict count protocol of all birds encountered
  - line transects, distance sampling, known survey effort
  - randomized site selection, high coverage (1.66% of UK!)







- Other (slightly less) structured schemes exist for waterbirds, shorebirds, seabirds, and garden birds

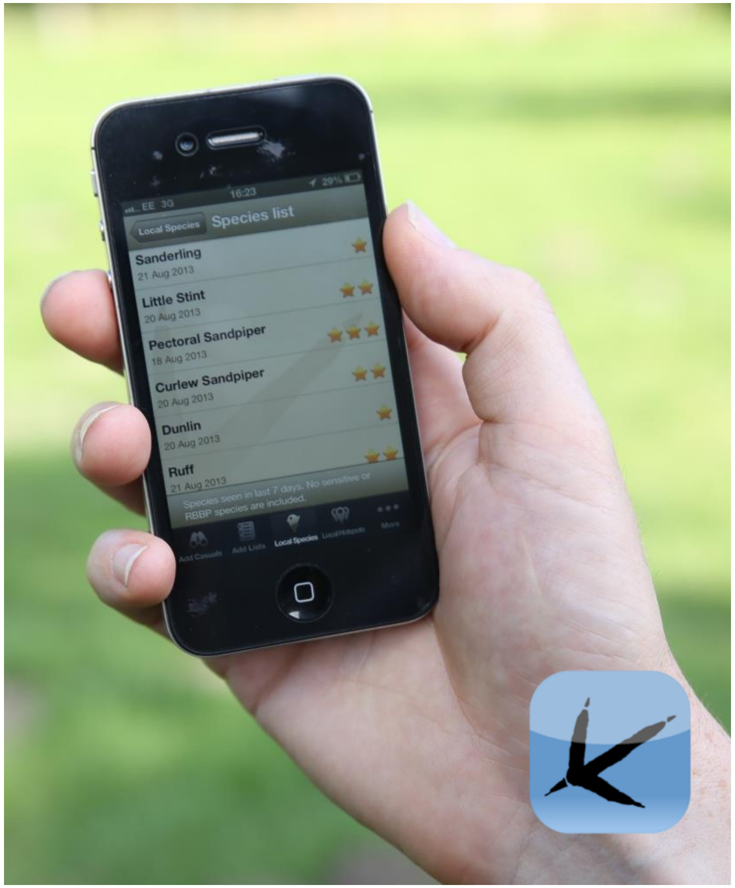
BirdTrack: Semi-structured bird recording

- Largest bird recording scheme in the UK
    - 2005-present
- Similar to eBird
- Data entry via app or web portal

- **BirdTrack delivers a lot of data**
    - **>15,000 locations/year**
    - **>100,000 lists / year**
        - **c. 10 million species records / year**

- BUT: No fixed observation protocol, no design
    - sites self-selected
    - complete listing optional
    - counting optional
    - effort recording optional

- Models are needed to account for the BirdTrack observation process



www.birdtrack.net

Bird Ringing


Image: DAVID TIPLING

- BTO issues ringers permits and oversees training in the UK
- Qualified ringers are free to ring at self-selected sites ("non-structured ringing")
- The Constant Effort Scheme is a site-specific structured scheme
  - mainly reedbed, scrub, woodland
  - 12 prescribed annual capture events, 10 days apart May-August
  - same nets in same positions
  - all captured birds are processed, focus on 24 songbird species
- Other structured schemes exist to target non-passerines

Ringing Schemes

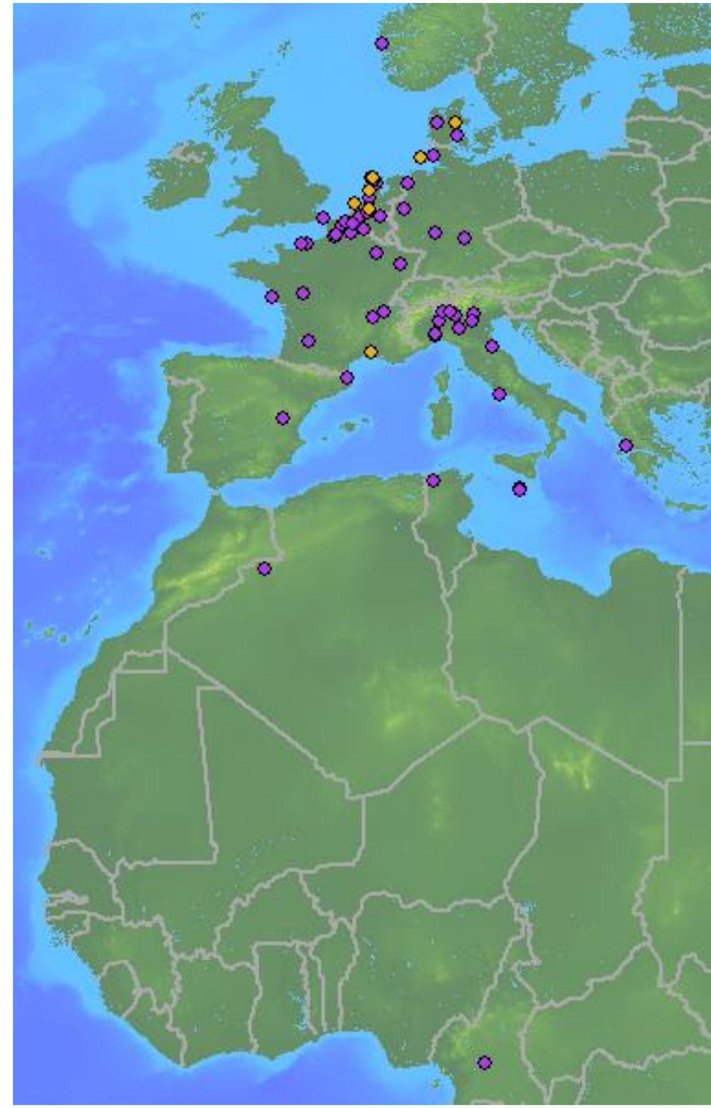
Ringing Scheme Objectives

- Measure change in local breeding population size
  - From adult capture rates
- Measure changes in productivity
  - From juvenile to adult ratios
- Measure survival and recruitment
  - From recaptures across seasons
- Collect biometric data
  - Body mass/measures, breeding status, plumage, etc


Image: DAVID TIPLING

Marking for large scale movements

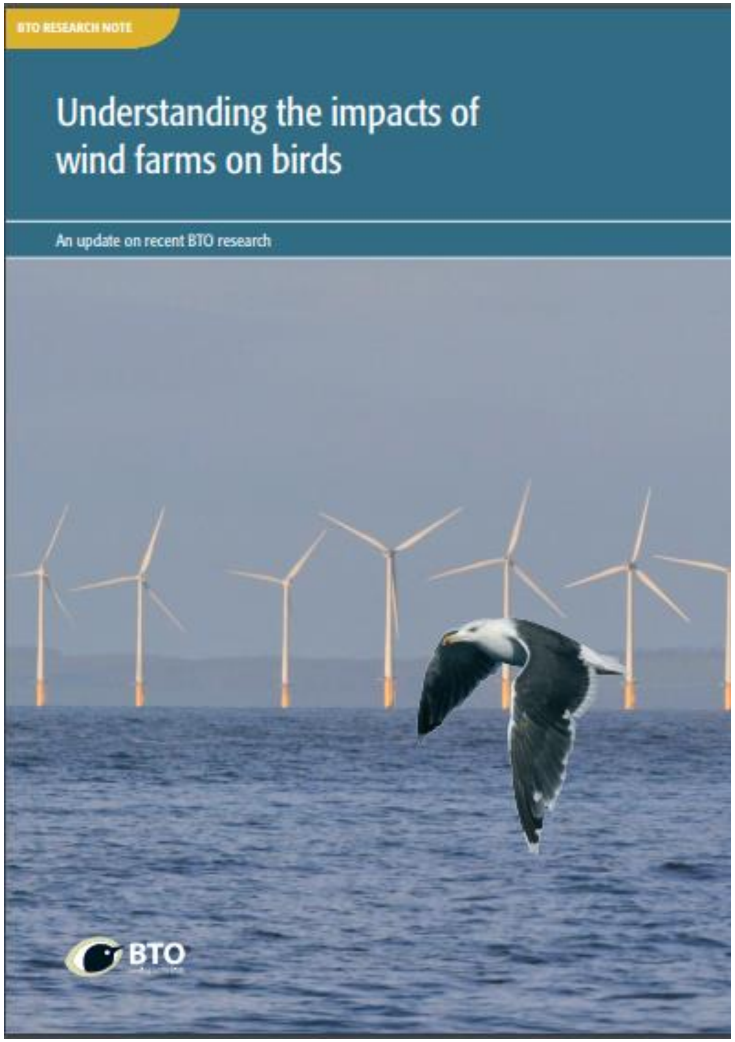
- Originally using ring recoveries/resights
- Now increasingly Geolocator/GPS tagging
  - e.g. Nightingales, Cuckoos, Nightjars, Gulls, Skuas



Marking for small scale movements

- Most work in renewables context
  - GPS/accelerometer/altimeter tags
  - Aerial LIDAR measurements
  - Foraging ranges of Urban Gulls
  - 3D space use of gulls in wind farms to assess collision risks

- Colour-ring mark-resight work to understand passerine home-range dynamics



Thaxter et al. 2018 Mar Ecol Prog Ser, Smith-Ross et al. 2016 J Appl Ecol, Johnston et al. 2014 J Appl Ecol

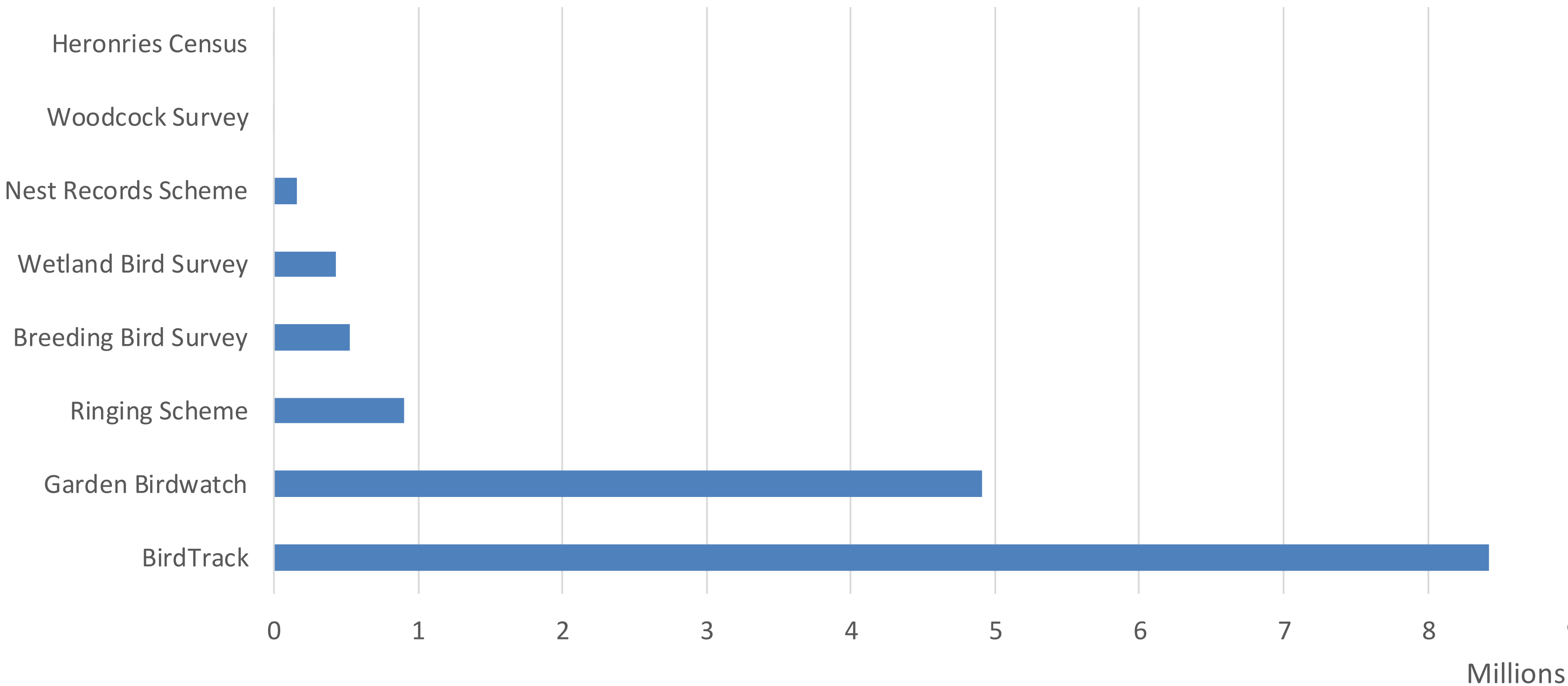
Nest Records Scheme

BTO

- Volunteer selected sites, species
- Multiple visits during the breeding season to record
  - Nest status
  - Numbers of eggs
  - Numbers of chicks
  - Fledging success
  - Ring nestlings
- Often chicks are ringed

BTO Nest Record Scheme

BTO volunteers collect a lot of data!



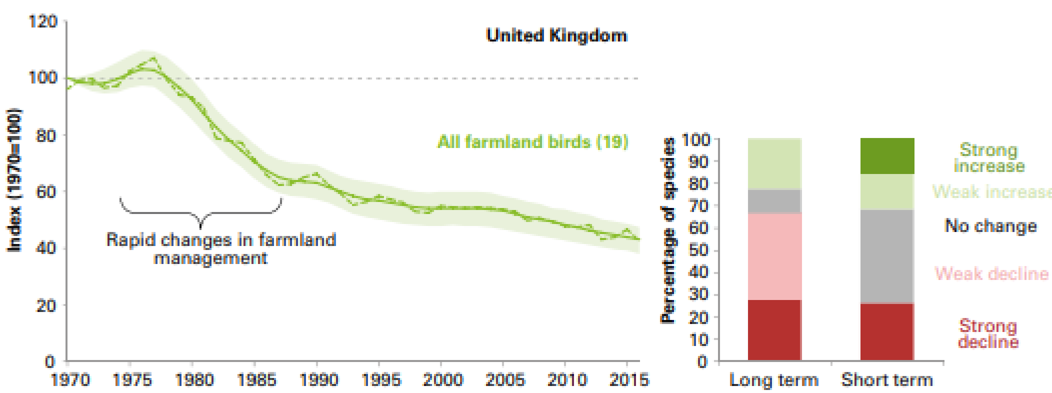
c. 2 million volunteer-hours in 2022

>15 million records in 2022

BTO data volume, main schemes, 2022

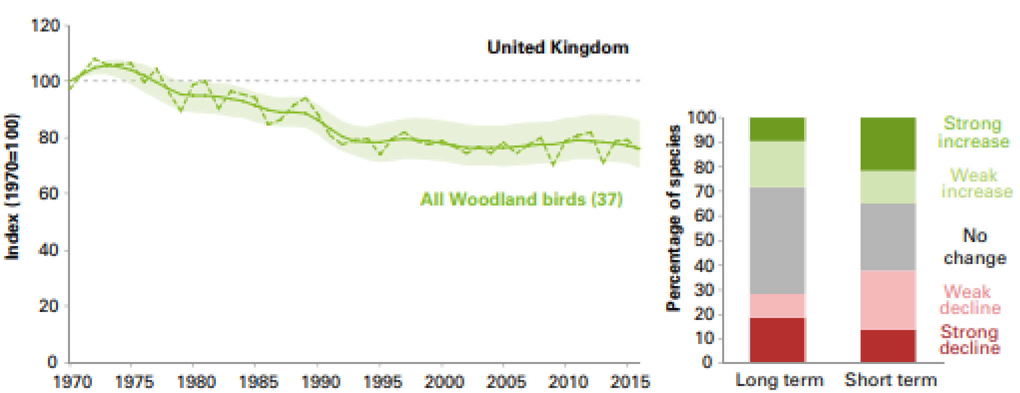
BTO data products – Species data

Breeding farmland birds in the UK, 1970 to 2016.

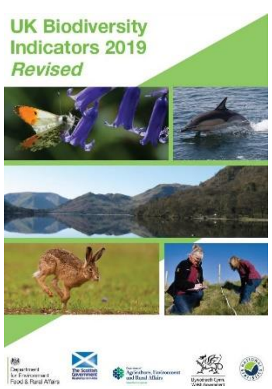


- Single species trends and Multi-species indicators are published annually
- Generally open data
- Some are official statistics
- widely used in policy and communication

Breeding woodland birds in the UK, 1970 to 2016.



State of the Birds 2017 – RSPB/BTO/WWT/DAERA/JNCC/NE/NRW



BTO data products – Species data

BTO's Trends Explorer

The Trends Explorer is an interactive tool for exploring how trends in UK bird abundance and other key measures are changing through time.

Trends are based on data collected by volunteers participating in surveys and schemes run by BTO and partner organisations.

The Trends Explorer accompanies BTO BirdFacts which provides key information about all UK bird species.

Use the controls below to select the trend you'd like to view. Where sufficient data exist you can see trends for individual countries. If required, you can download the graph and underlying data.

Pick a species

Pied Flycatcher

Pick a trend type

Population abundance

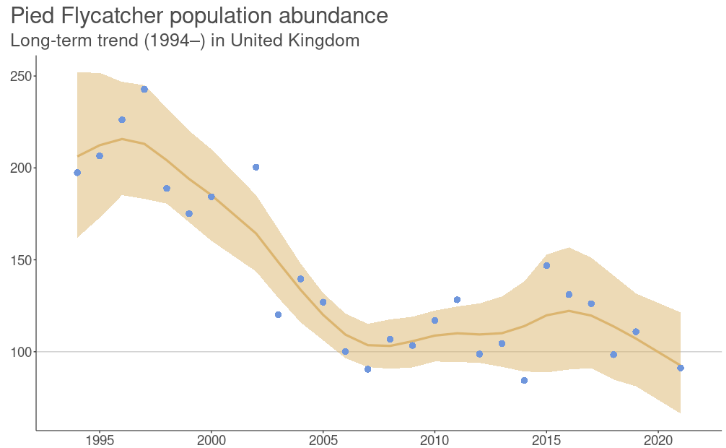
Pick a specific trend

Long-term trend (1994–)

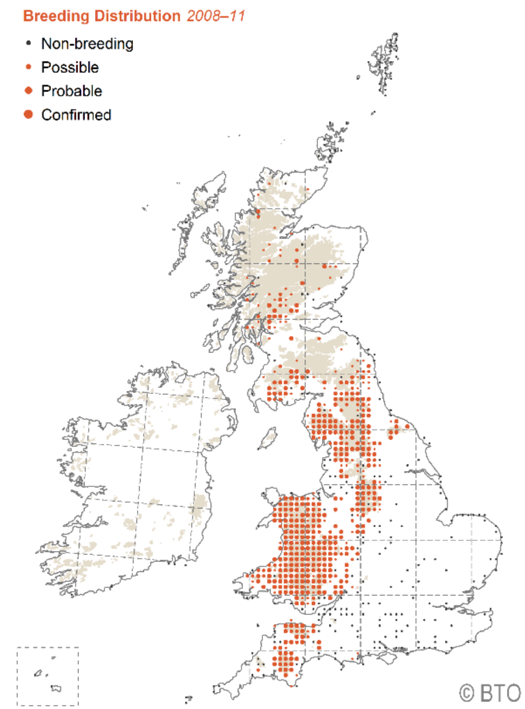
Pick a country

United Kingdom

Make Plot



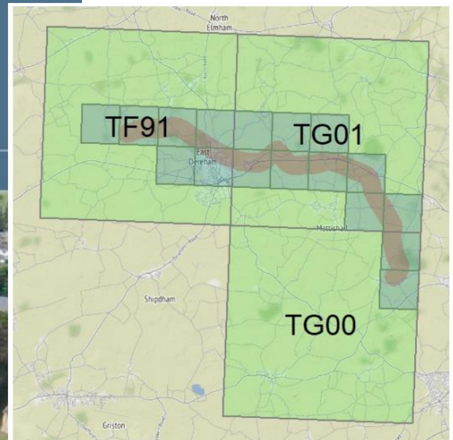
The smoothed **trend line** shows how the number of birds has changed through time. To make it easier to compare among species, this is expressed as an 'index', set to 100 in the penultimate year. An easy way to interpret this is to say for every 100 birds present now, the trend line shows how many were present in a previous year. The **shaded area** shows uncertainty around



- Trends and 10km scale distribution data are open data
- Underlying survey datasets generally free for research use

BirdTrends, BirdAtlas: Gillings et al. 2019 Global Ecol Biogeog

BTO data products - Sites



Species category	2-km	10-km	20-km	50-km
All species	72	25	0	4
Annex 1	1	3	0	4
BoCC Amber	20	7	0	2
BoCC Red	16	7	0	2
IUCN2 Critically Endangered	1	1	0	2
IUCN2 Endangered	3	3	0	1
IUCN2 Near Threatened	10	4	0	0
IUCN2 Vulnerable	13	5	0	1
RBBP	1	7	0	4
Schedule 1 UK	2	7	0	3
Schedule ZA1 England & Wales	0	0	0	0
Section 41 England	16	4	0	0

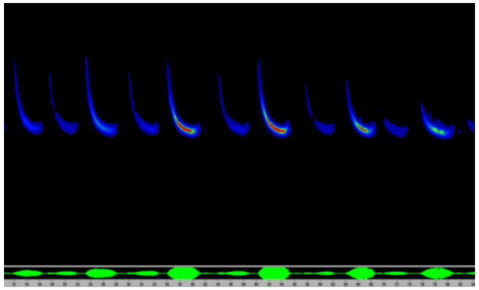
- Breeding range, one species: Marsh Warbler
- Winter range, two species: Black-throated Diver, Lesser Spotted Woodpecker
- Breeding abundance, three species: Water Rail, Sand Martin, Spotted Flycatcher
- Winter abundance, four species: Mandarin Duck, Rook, Woodlark, Yellowhammer

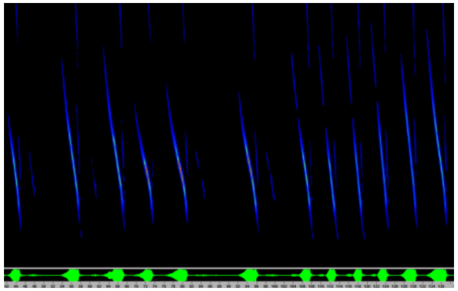
- Commercial data product for Ecological Impact Assessments
- Collates historical BirdAtlas and current records (last 5 years)

BTO data products – Acoustic classifiers

- No formal acoustic bird monitoring scheme yet
- Regional bat/bird project work

- **Acoustic Pipeline:** Cloud-platform for acoustic data analysis
- Acoustic classifiers for high-frequency and audible sound
  - Bats
  - Small mammals
  - Insects
  - Nocturnal birds
  - Nocturnal flight calls
  - Soon: Daytime bird song
- Multi-species analysis
- Free for personal use
- Data for research and conservation
- Paid tier for commercial use



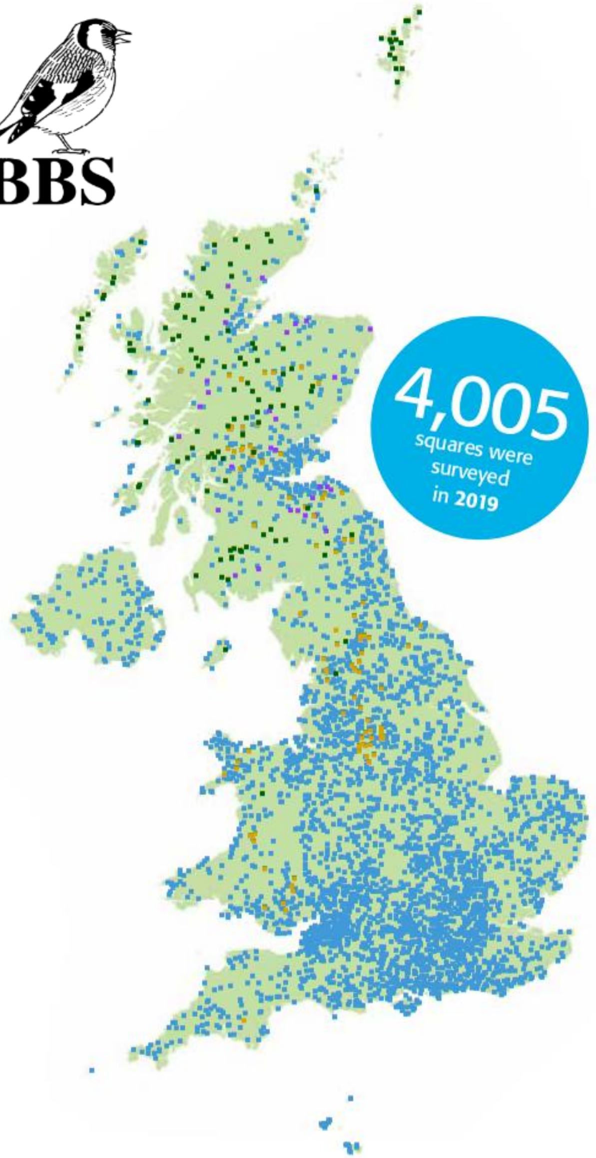


Case study 1:

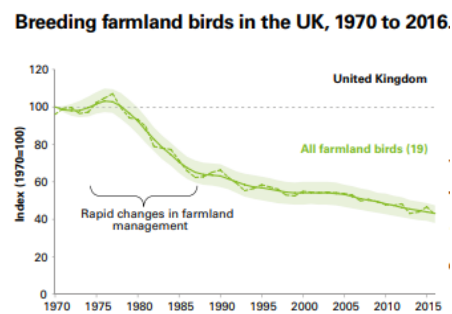
Integrating data sets for small area trends

Bird monitoring in the UK

BBS



- UK Breeding Birds Survey (BBS) forms the backbone of terrestrial breeding bird monitoring
- Effective coverage >1.5% of the land surface
- UK trends for ~120 species
- Trends feed into statutory reporting, biodiversity indicators and many other applications



BBS Abundance Trend Model

- BBS trends are based on a Poisson GLM which treats years and sites as categorical covariates and uses the number of transect segments as an offset

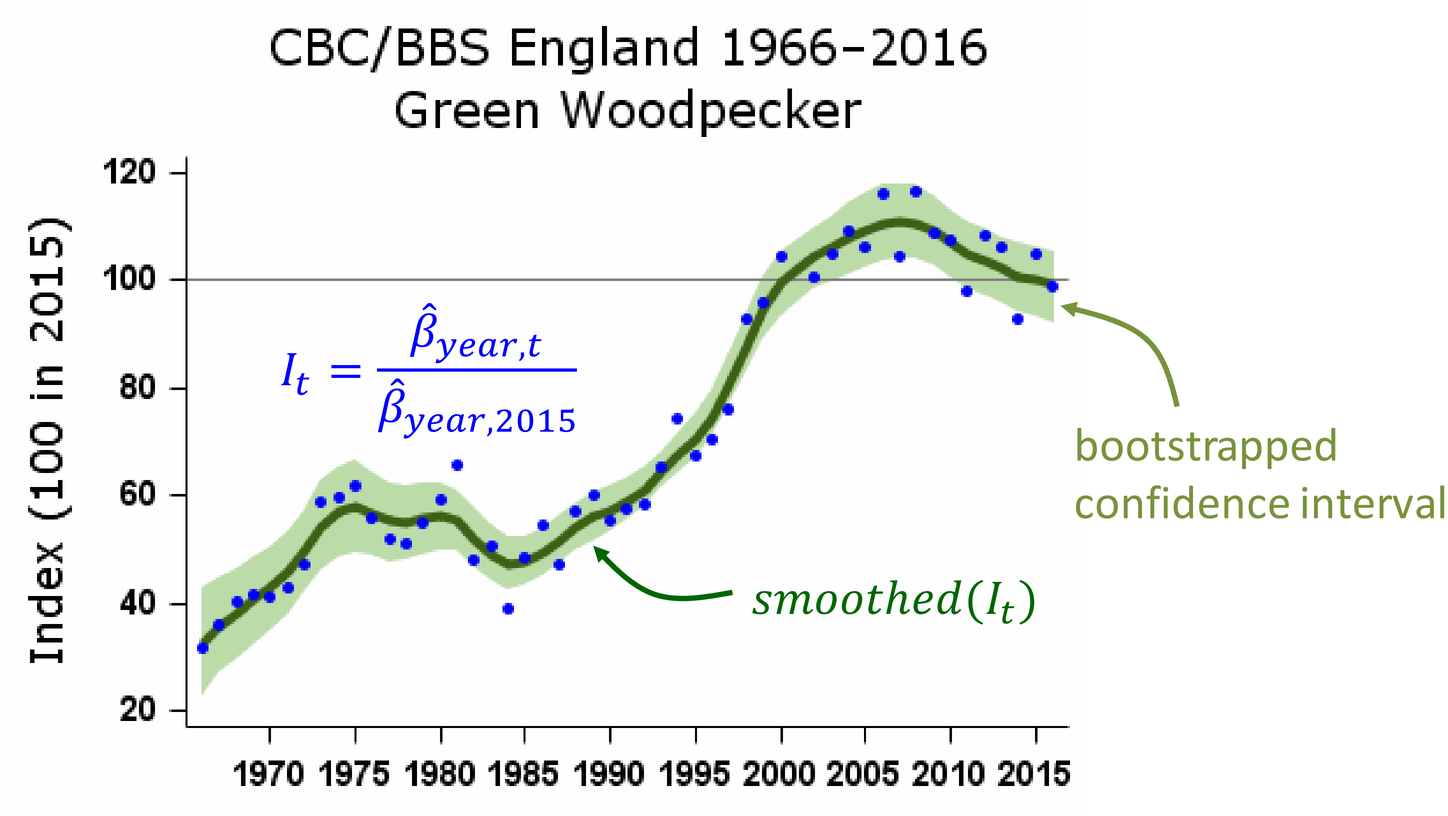
$$N_{max,it} \sim Poisson(\lambda_{it})$$
$$\log \lambda_{it} = \beta_{year,t} + \beta_{site,i} + \log N_{segments,i}$$

- Observations are weighted to account for uneven observer availability across the UK
- weights = inverse sampling probability within stratum – these weights are known precisely from the survey design

- Relative abundance indices $I_t = \dfrac{\widehat{\beta}_{year,t}}{\widehat{\beta}_{baseline\,year}}$
- I_t are smoothed post-hoc to highlight longer term patterns

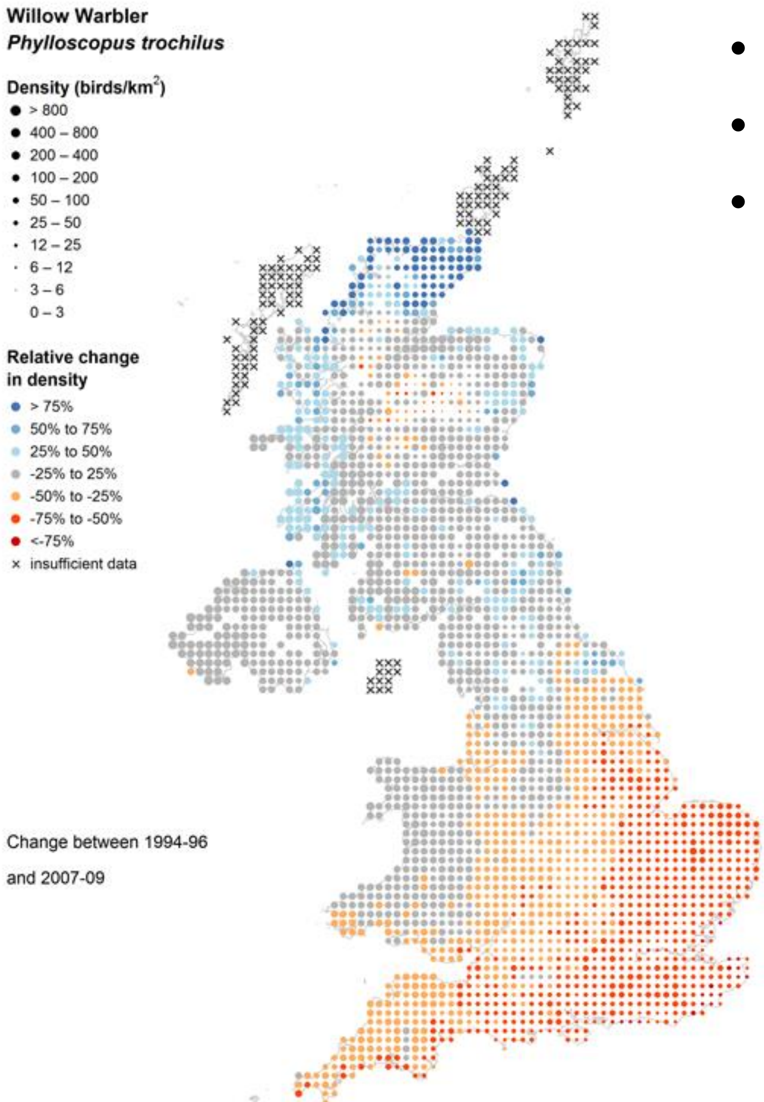
Fewster et al. (2000) Ecology

BBS Trends

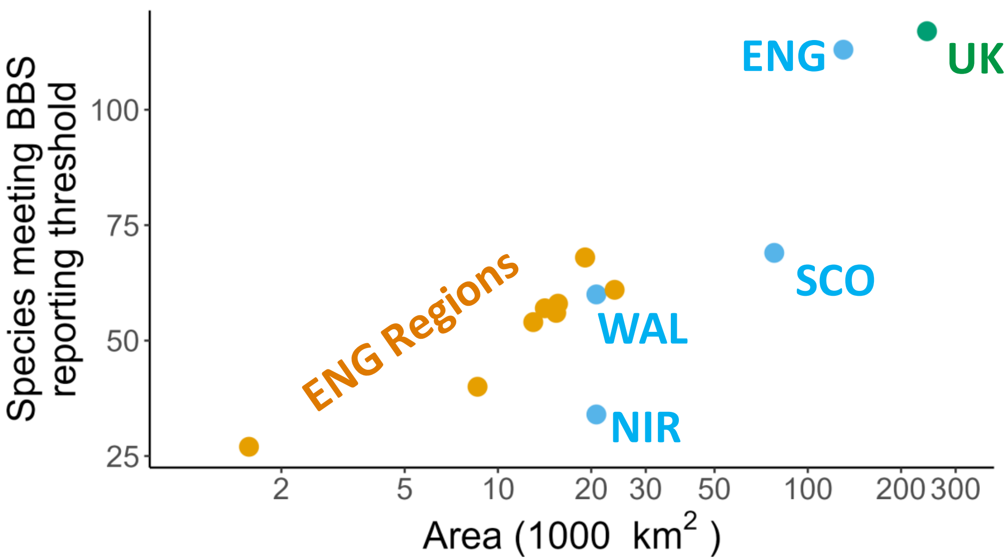


- BBS index: average count relative to a baseline year (here 2015) $I_t = \frac{\widehat{\beta}_{year,t}}{\widehat{\beta}_{year,2015}}$
- Index values are smoothed using a regression spline to highlight longer term (3-5 year) population change rather than year-to-year variation

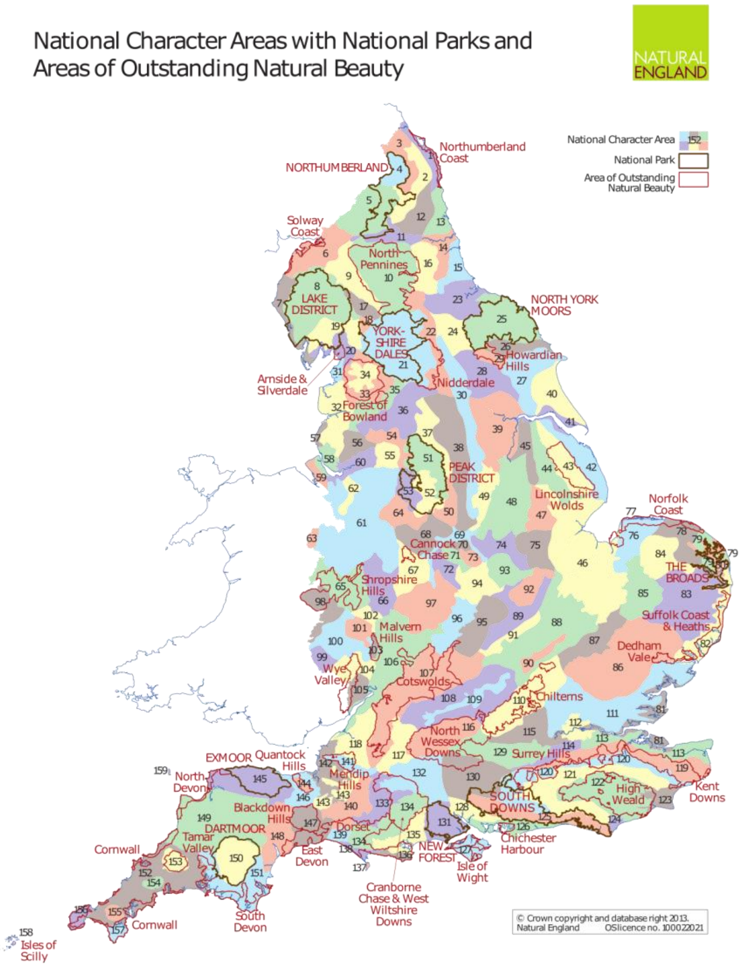
Regional bird trends



- Trends are not homogeneous across the UK
- Neither are policy/management structures
- Current approach to country-level and regional trends is a cookie cutter approach:
  - Trend models fitted to geographic subsets
  - Sample size thresholds ensure statistical robustness



Regional bird trends



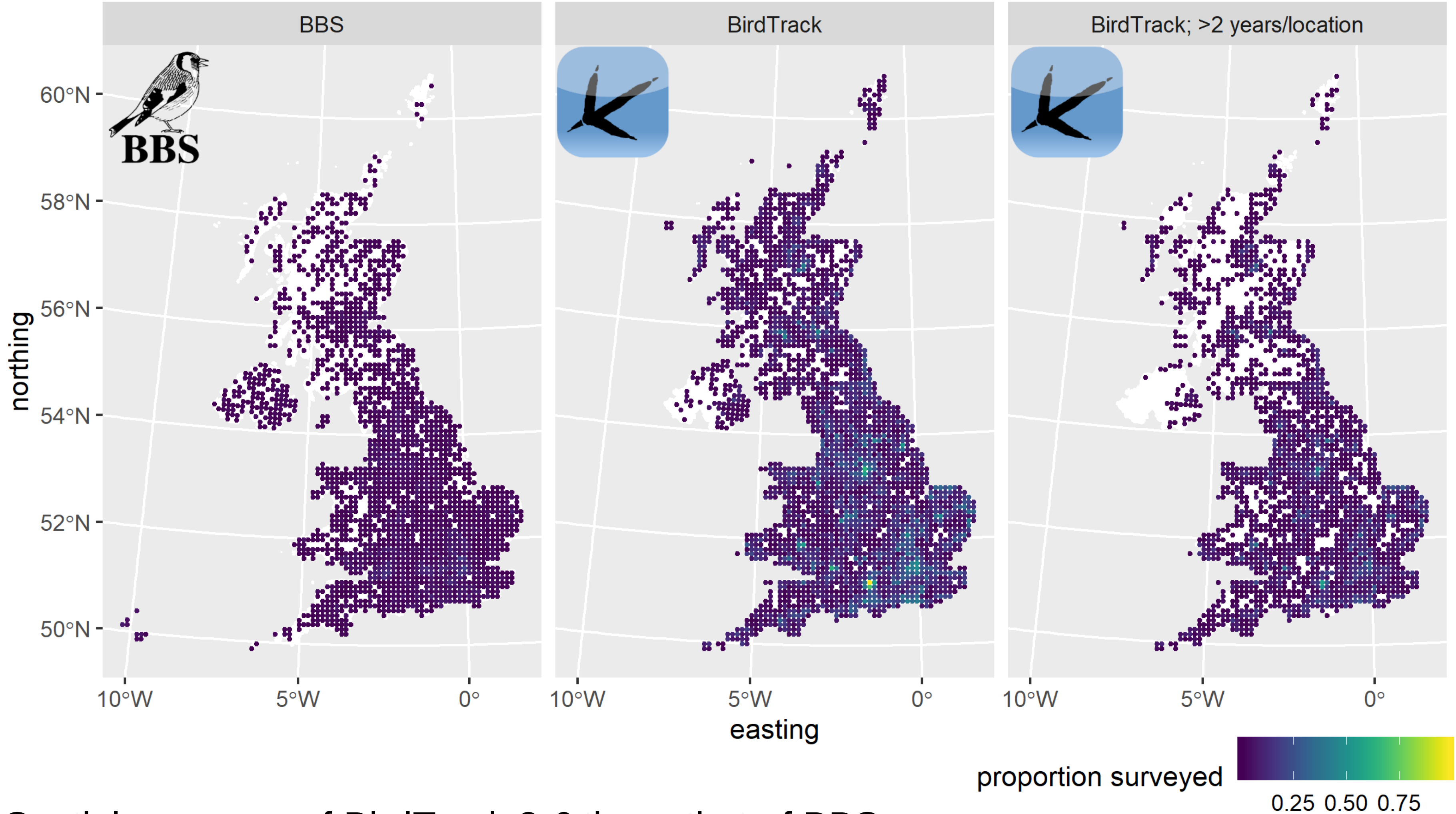
- Conservation policy and management are increasingly devolved or take place-based approach
- Different spatial units of interest (e.g. jurisdictions, national parks, landscapes)
- National surveys are not designed to deliver inferences at these spatial scales
- Current cookie cutter approach not useful for increasingly smaller areas of interest

Natural England

Limitations of BBS Trends

- BBS Trends are designed for inferences at UK/country level
  - Many end-users would like small area trends to inform management.
- BBS designed to capture abundant and widespread species (~120 species trends reported)
  - Many species of conservation concern are not abundant or widespread

Bird data: Gaps and sample sizes

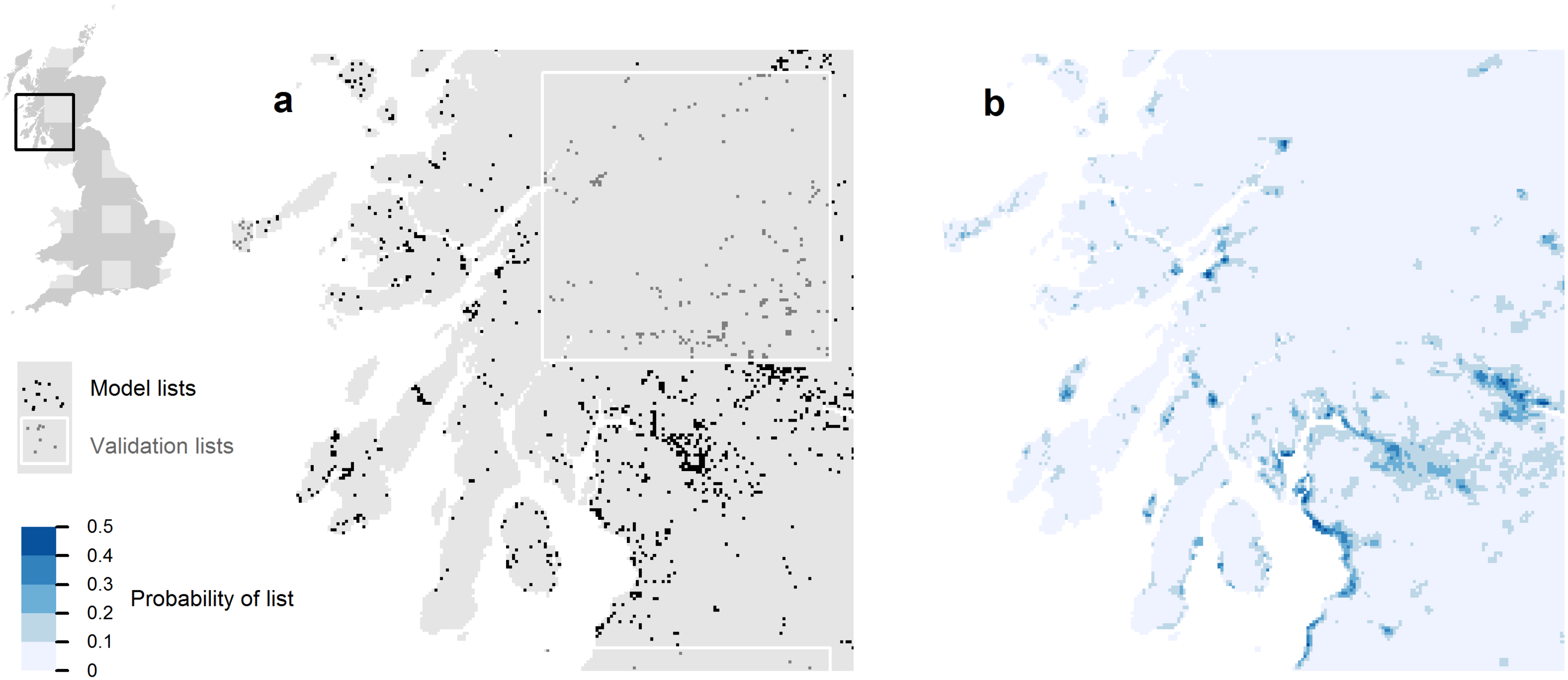


Spatial coverage of BirdTrack 3-6 times that of BBS
Gaps in both schemes: Uplands (Scotland, central Wales)
Gaps in BirdTrack: Rural Northern Ireland, areas w/ high-intensity agriculture

Boersch-Supan et al. 2019 Biological Conservation
https://doi.org/10.1016/j.biocon.2019.108286

BirdTrack sites are not randomly selected

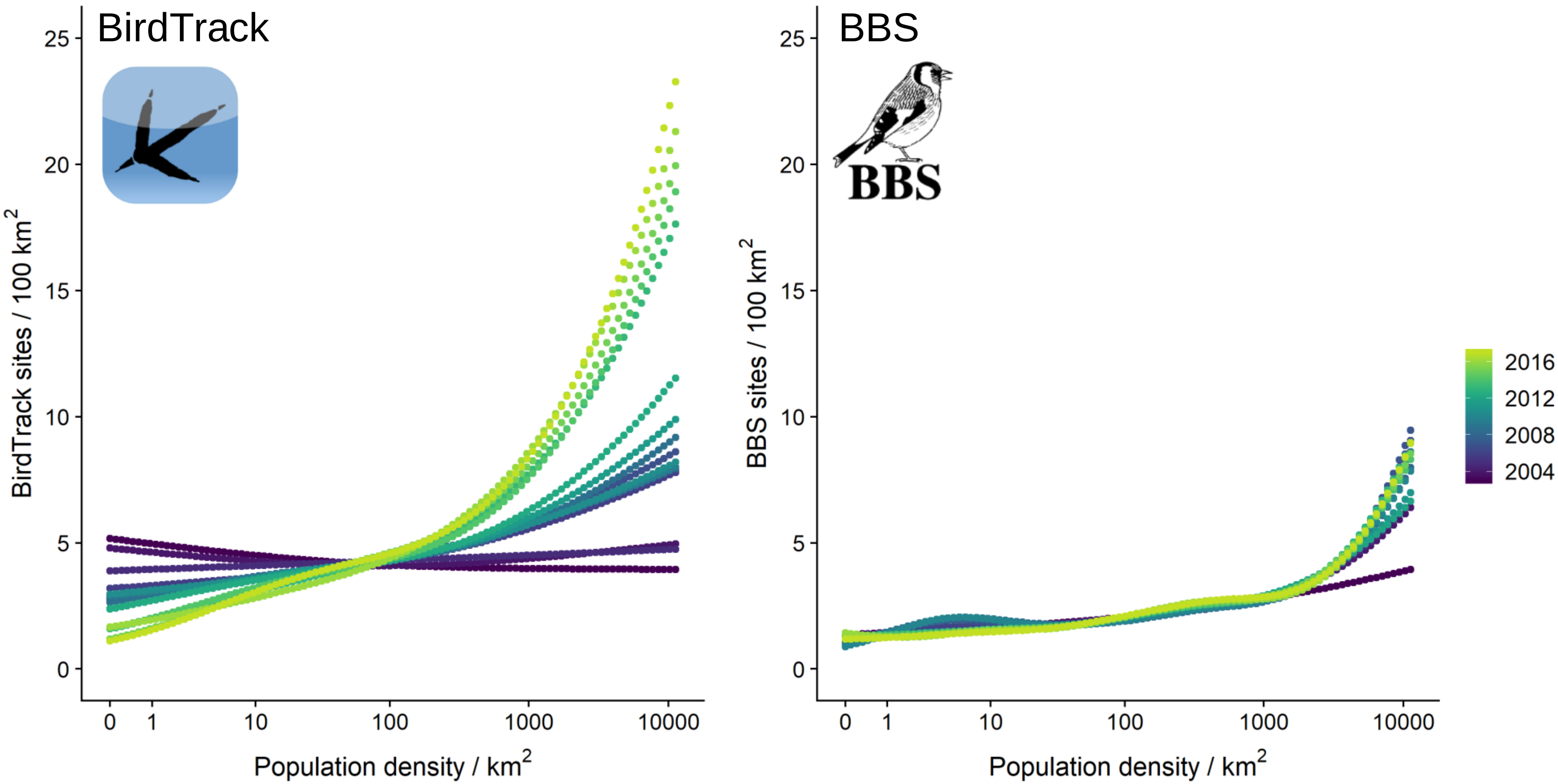
BirdTrack sites are biased towards urban areas, coasts, reserves



Johnston et al. 2020 Ecological Modelling

Site selection bias is non-stationary

BirdTrack spatial bias is *increasingly* urban

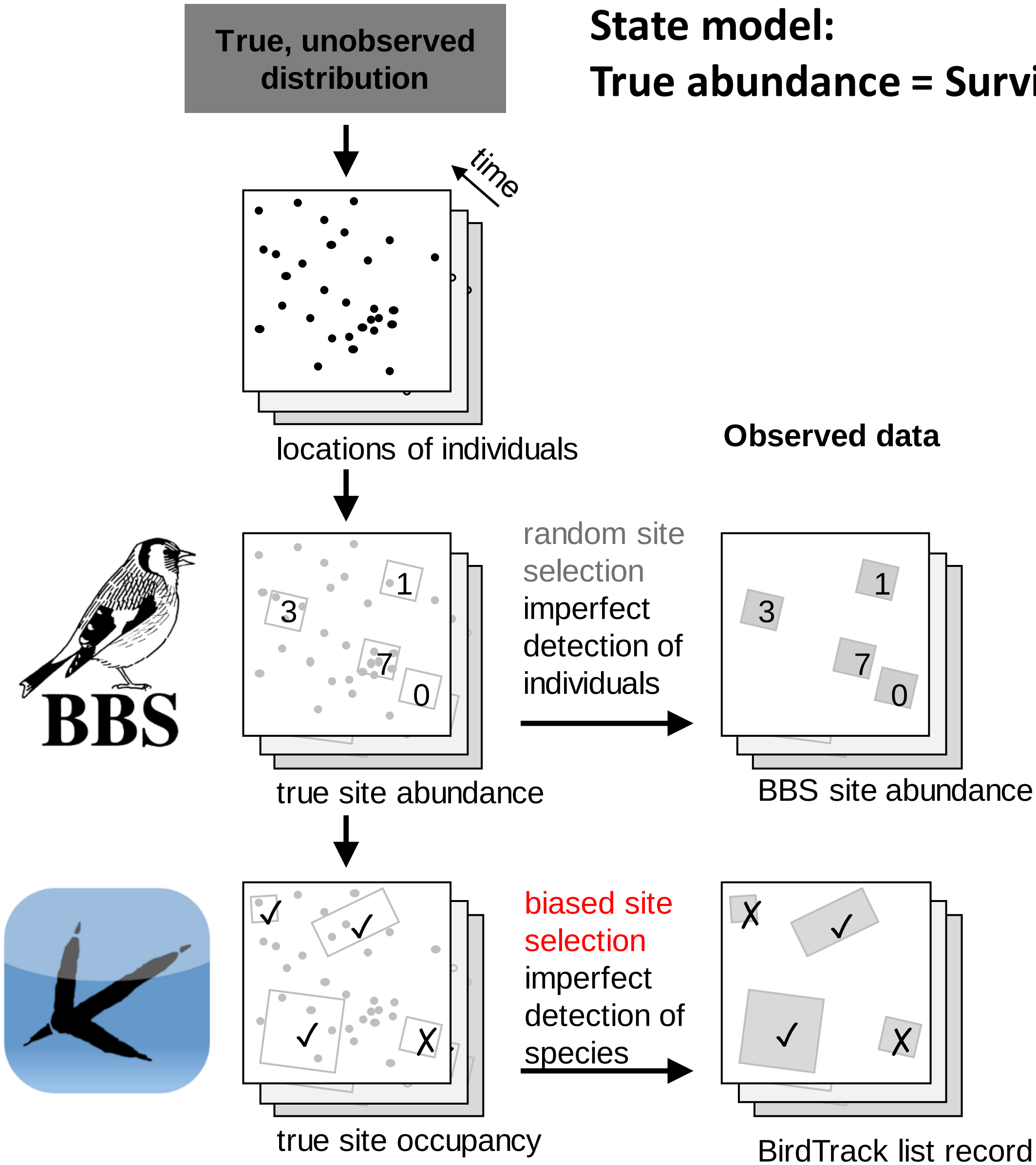


Boersch-Supan et al. in review.

Integrated abundance model

State model:

True abundance = Survival + Recruitment

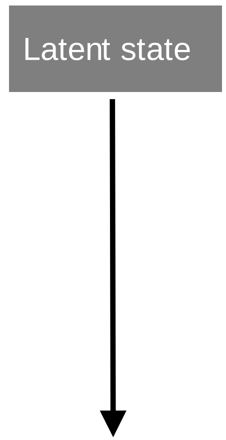


count data
unbiased sampling
standardized effort
but “small” sample size

presence/absence data
biased sampling
variable effort
large(r) sample size

after Isaac et al. 2019 Trends Ecol Evol
https://doi.org/10.1016/j.tree.2019.08.006

Integrated abundance model

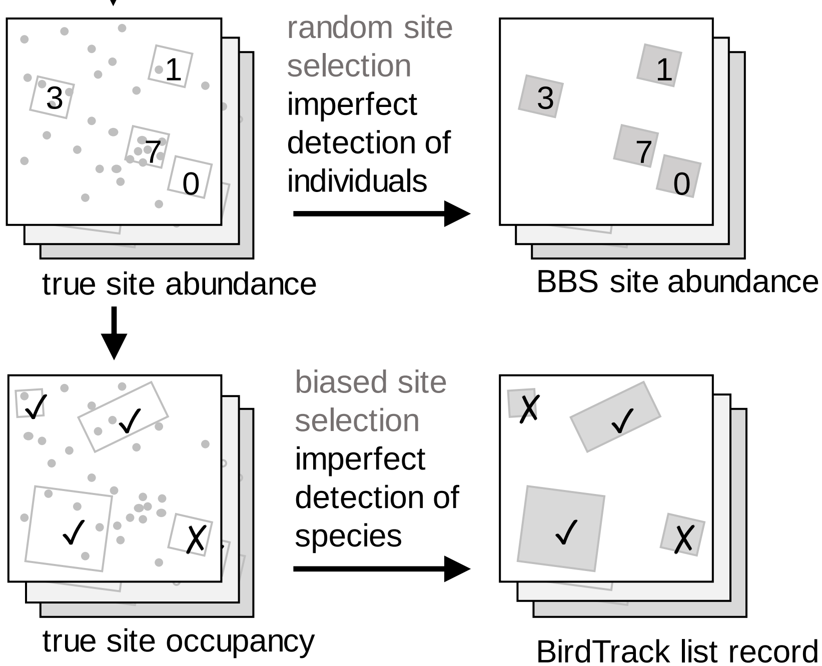


State model: True abundance = Survival + Recruitment

$$N_{j,t} = S_{j,t} + G_{j,t}$$

$$S_{j,t} \sim \text{Binomial}(N_{j,t-1}, \omega) \qquad \text{logit}\left(\omega_{j,t}\right) = \beta_{\omega} + \cdots$$

$$G_{j,t} \sim \text{Poisson}(\gamma)$$



Count observations: N-mixture model

$$n_{j,t,k} \sim \text{Binomial}(N_{j,t}, p)$$

Species list observations:

$$y_{j,t,k} \sim \text{Bernoulli}(1 - (1 - p_{occ})^{N_{j,t}})$$

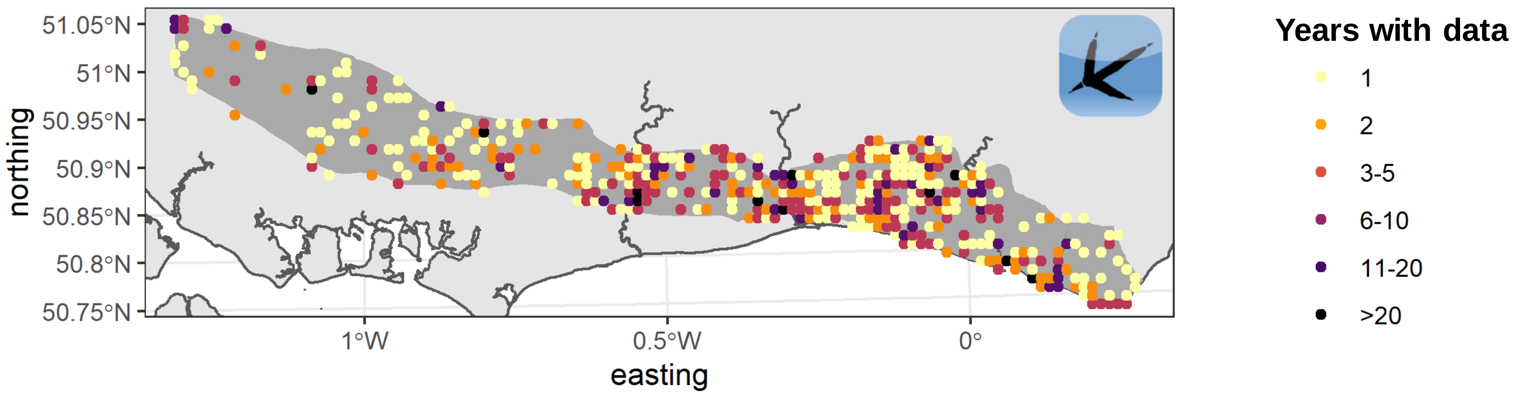
Boersch-Supan & Robinson 2021 bioRxiv., Zipkin et al. 2018 Ecology

Case study: Corn Bunting in the South Downs

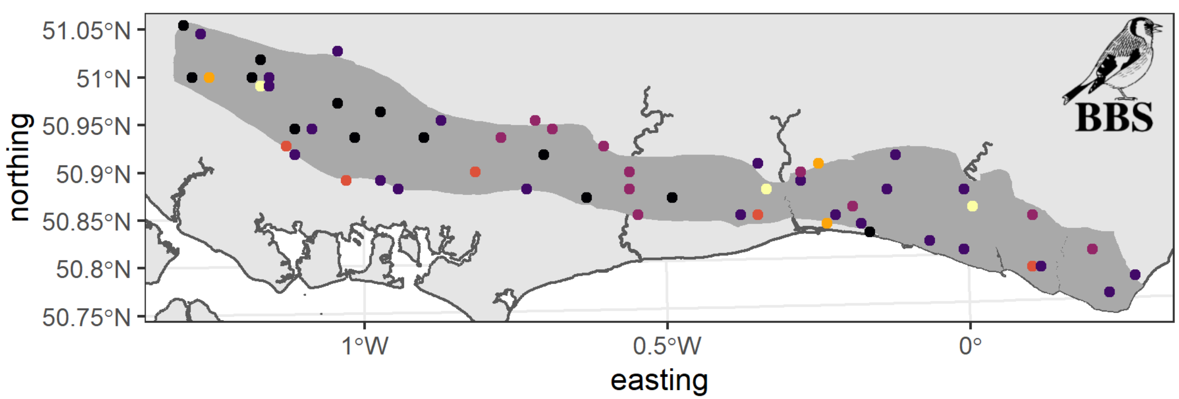
Can we use data integration to get trends for small areas?

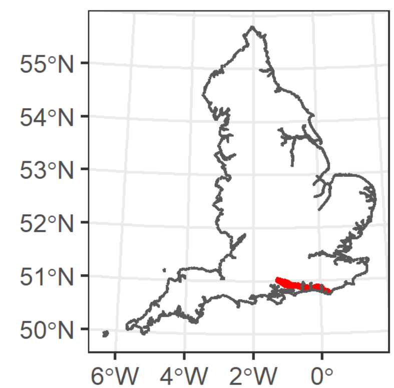
South Downs National Character Area

BirdTrack 2002-2018

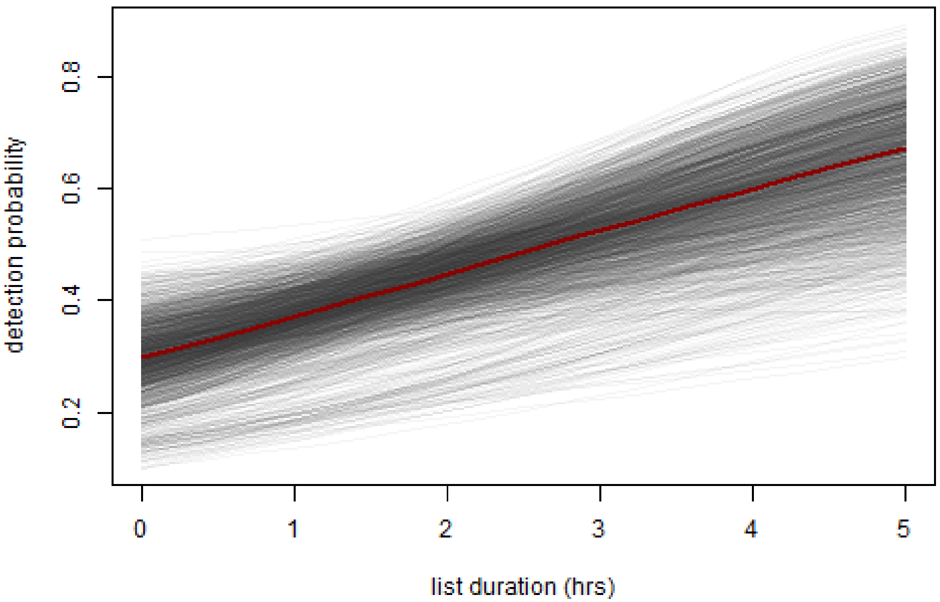


BBS 1994-2018

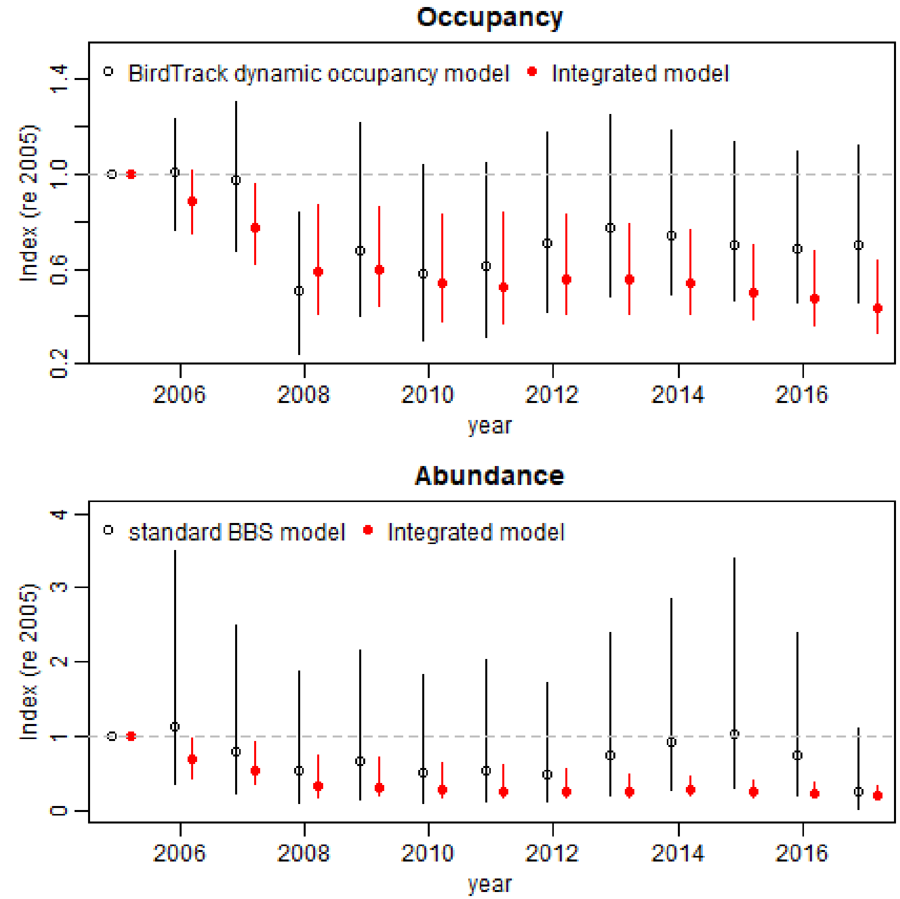




Case study: Corn Buntings in the South Downs



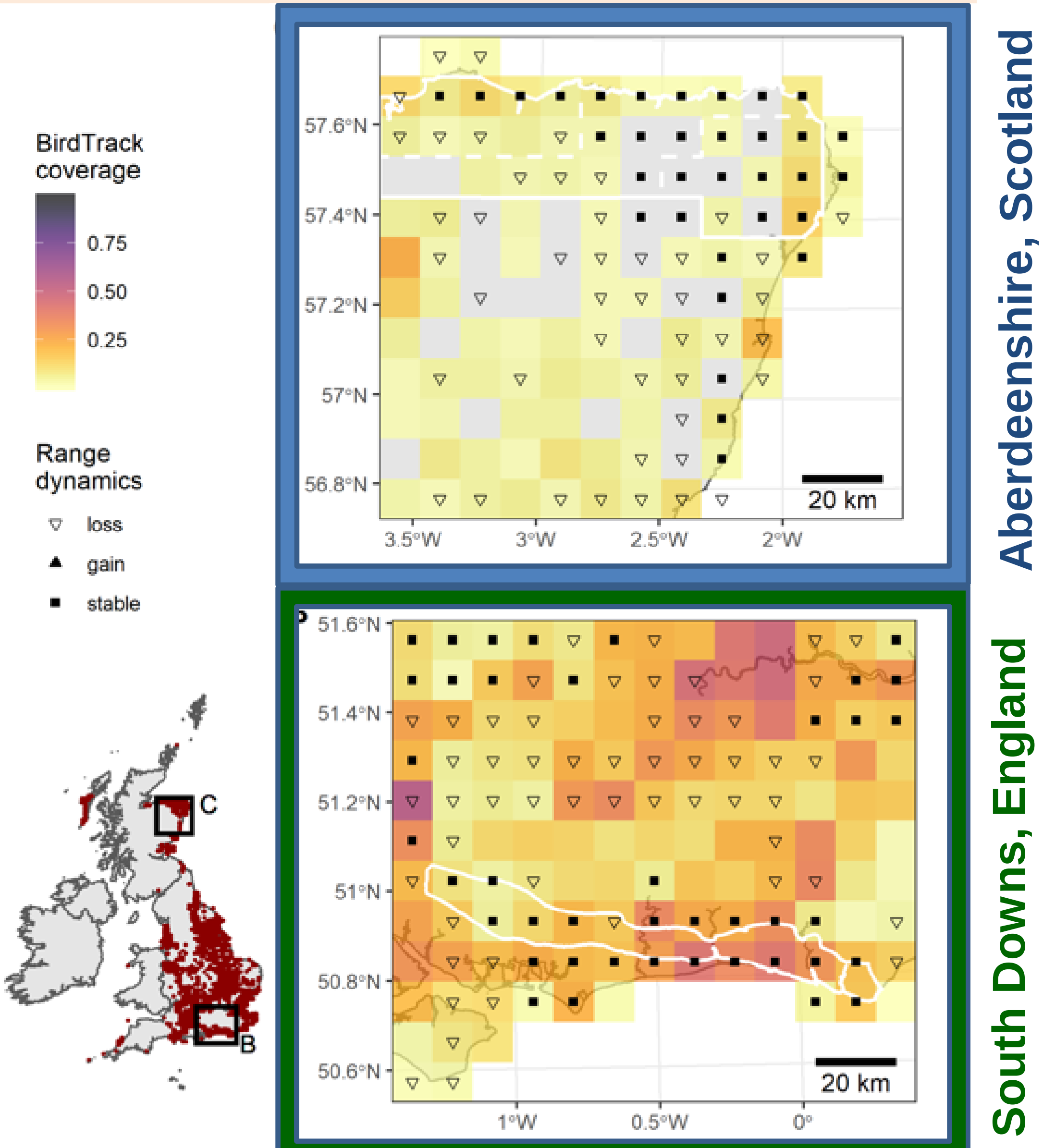
Integrated model accounts for heterogeneous observation effort in BirdTrack data

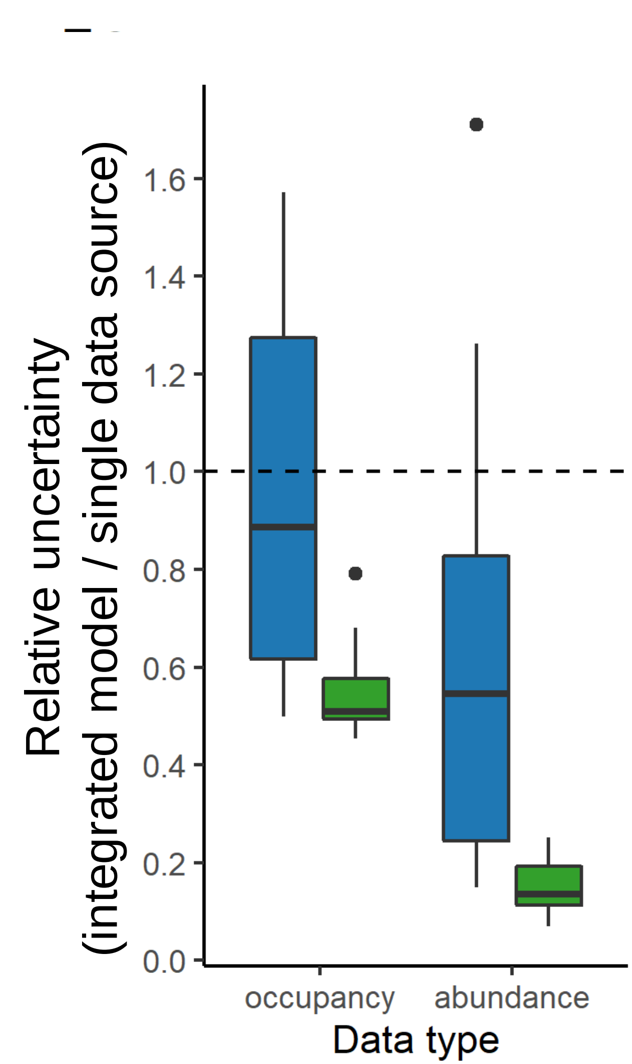


Precision of integrated trend estimates is better than using either dataset alone

Boersch-Supan & Robinson 2021 bioRxiv

Corn Buntings in Scotland: Data Gaps





Boersch-Supan & Robinson 2021 bioRxiv

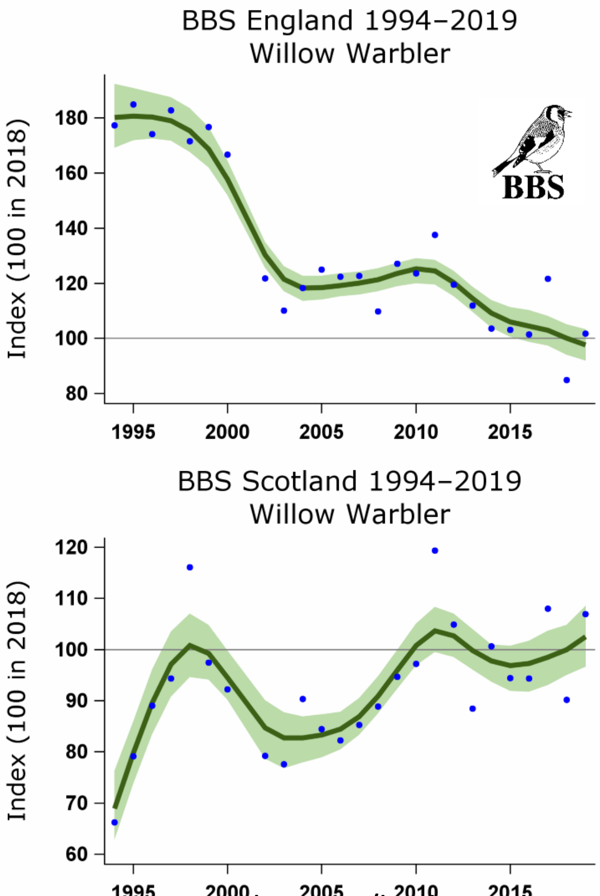
Integrated trend models

- Opportunities of integrated modelling
  - leverage strengths of both structured and unstructured data
  - great potential to improve precision of regional bird trends (~1000-10,000 km^2)
- Challenges of integrated modelling
  - formally addressing site-selection bias remains a challenge
  - no simple, one-size-fits-all approach: models require customization for each application
  - No easy way to diagnose goodness of fit, overfitting, etc.
  - Some species and/or areas will be better suited than others
- Implications for scheme design
  - encourage recording of effort
  - encourage complete list recording
  - can we encourage recording in "boring areas"?

Case study 2:

Shedding light on drivers of population change

Other mechanistic insights



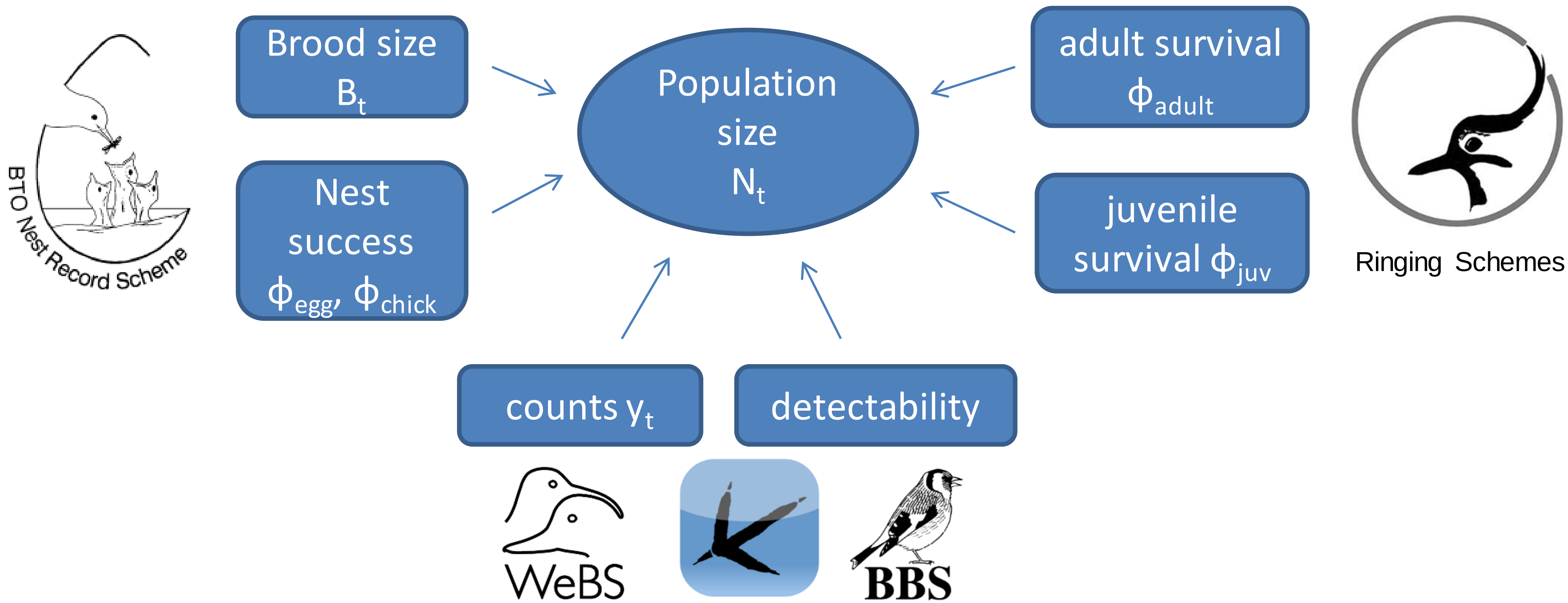
www.bto.org/bird-trends

- **What drives population declines in English Willow Warblers?**

Hanmer et al. 2022 Biol Letters

Integrated Population Monitoring

- **Mechanistic population dynamics** models that integrate different data sources to make inferences about demographic processes



State/process model $$N_{t+1} = \underbrace{N_t\rho_t(B_t\varphi_{egg,t}\varphi_{chick,t}\varphi_{juv,t})}_{\text{recruitment}} + \underbrace{N_t\rho_t(\varphi_{adult,t})}_{\text{survival}}$$

Observation model, e.g. $y_t \sim \mathcal{F}(N_t, \sigma)$

Robinson et al. 2014, Methods Ecol Evol

Nater et al. 2023 J Anim Ecol

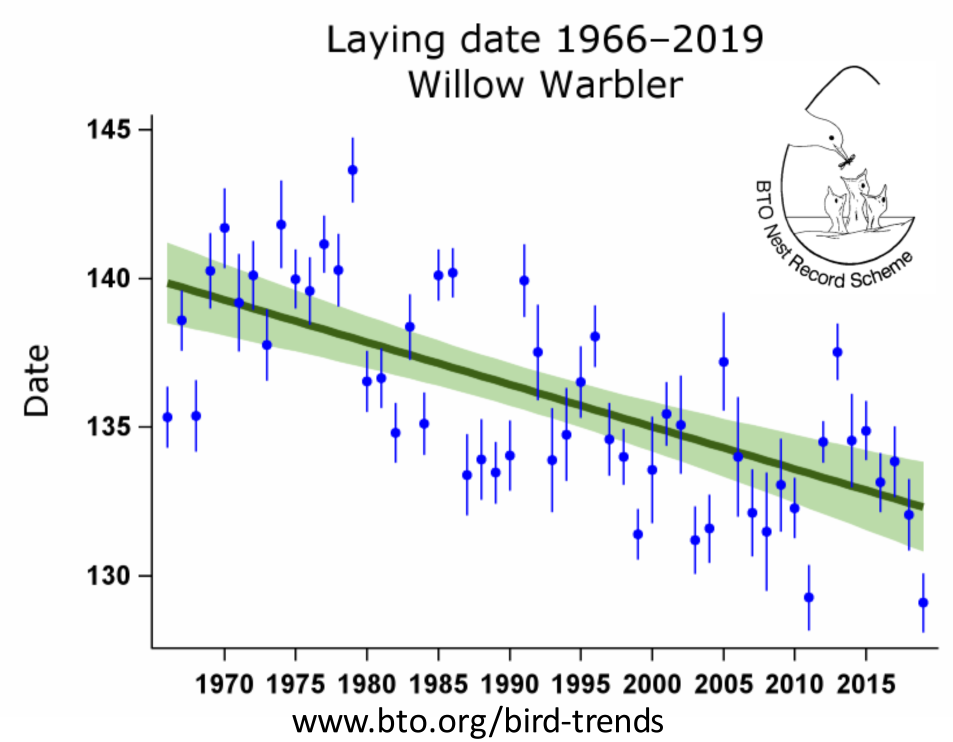
Integrated Population Monitoring

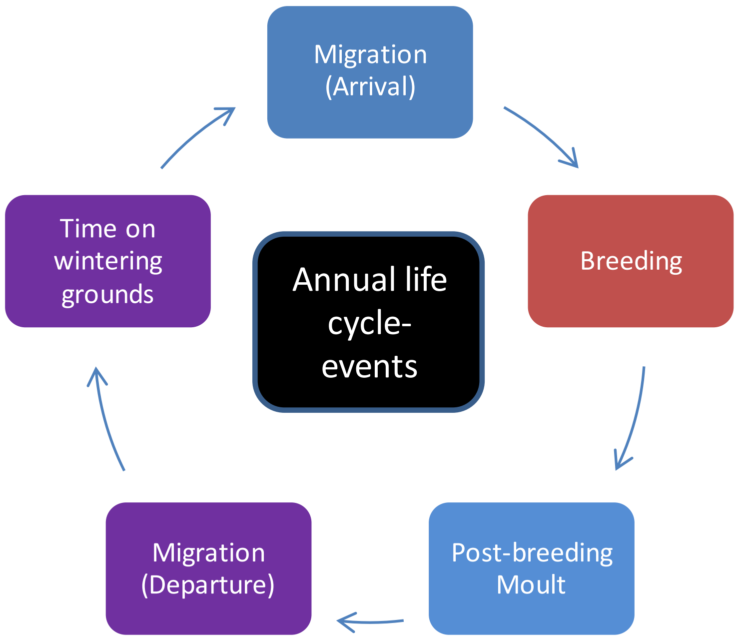
- IPMs are great, because they can quantify vital rates that can identify mechanisms of population dynamics
  - More information for targeting conservation action
- **But** IPMs are data hungry
  - In the UK we can fit them for at best c. 20 species
  - Willow Warbler is not one of them
- Vital rates alone may not be sufficient to inform optimal conservation action, but can identify further research priorities

Robinson et al. 2014, Methods Ecol Evol

Nater et al. 2023 J Anim Ecol

Other mechanistic insights





- We can't fit an IPM, but we do know reproductive rates are declining

Morrison et al. 2016 Proc B, Hanmer et al. 2022 Biol Letters

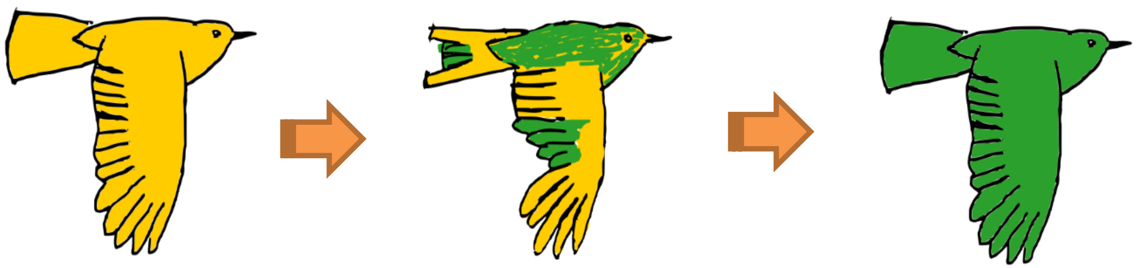
Other mechanistic insights

- Phenological analysis of nest records and biometrics from ringing
  - Egg laying, end of incubation (brood patch), feather moult

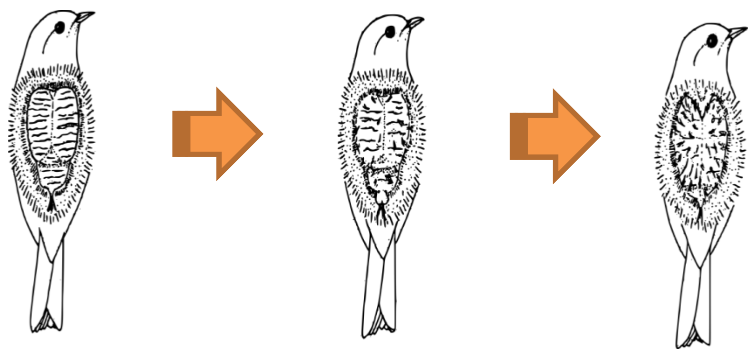
Hanmer et al. 2022 Biol Letters

Modelling unobserved transition dates

e.g. birds in old plumage, active moult, new plumage



e.g. brood patch formation and/or refeathering



Ordinal regression models for categorical data

Interval-censored regression for mixed categorical/continuous data

Boersch-Supan (2021) ReScience C; Boersch-Supan et al. (2022) arXiv

Underhill-Zucchini moult model

Parameters of biological interest are
start date,
population SD of start date
duration

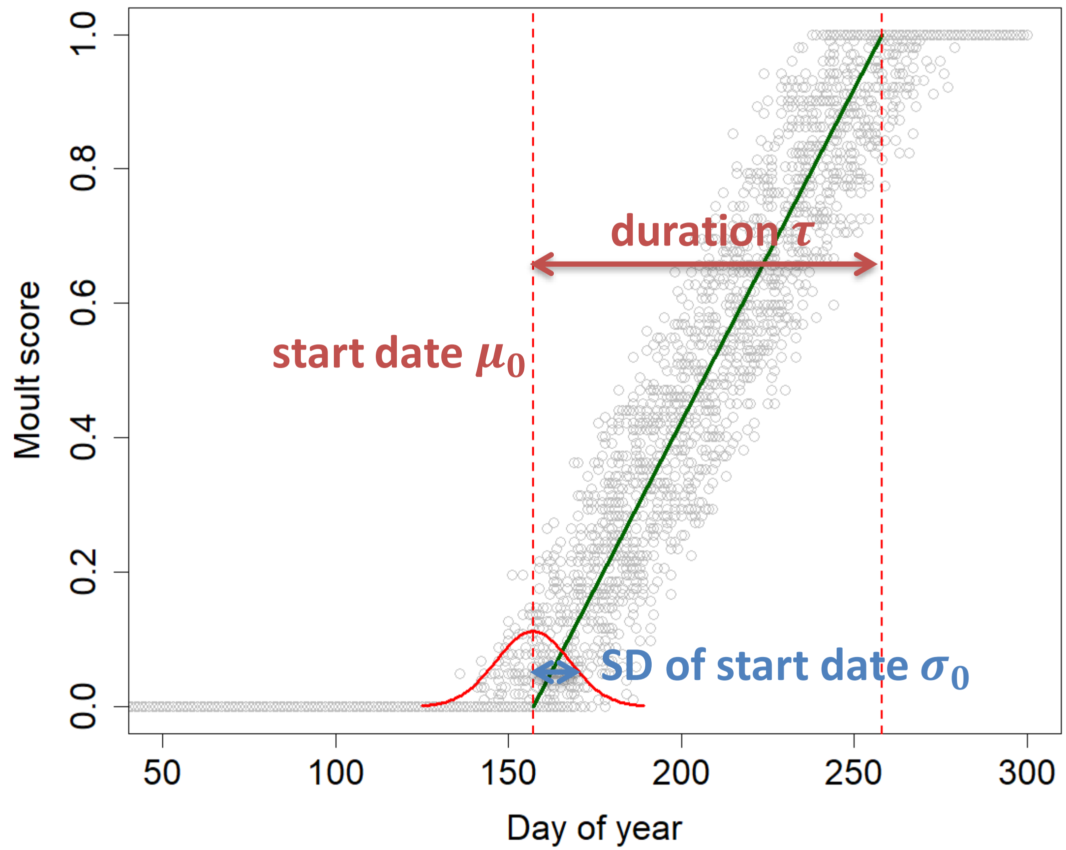
Inference possible using a form of censored regression (tobit-like)

$$\mathcal{L} = (1 - F_T(t|old)) \times$$ categorical $\mathfrak{L}$ on 'old' dates

$$(\tau f_T(t - score \times \tau)) \times$$ linear $\mathfrak{L}$ on active scores

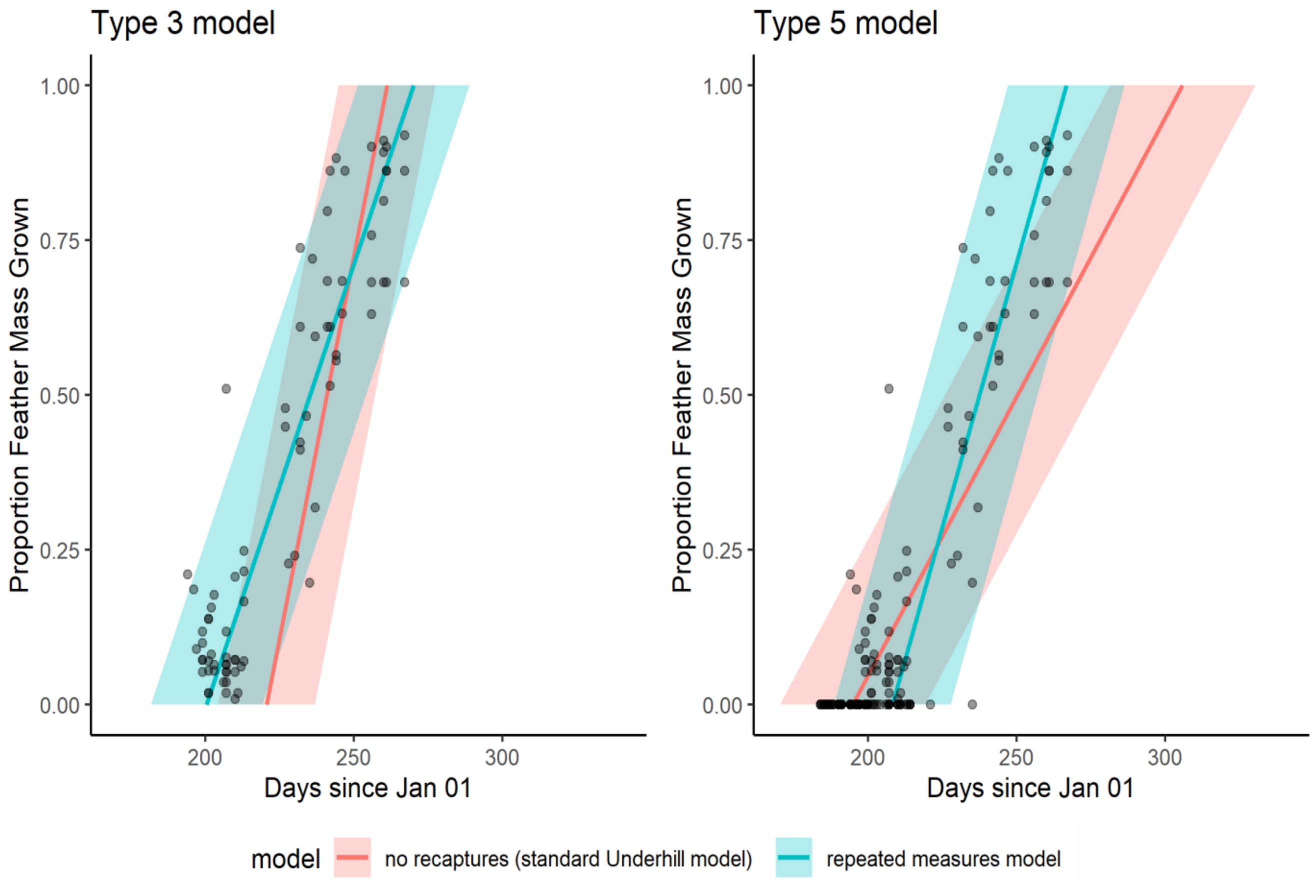
$$F_T(t - \tau|new)$$ categorical $\mathfrak{L}$ on 'new' dates

where f_T typically $Normal(\mu_0, \sigma_0)$



Underhill & Zucchini (1988) Ibis; Erni et al. (2013) J Stat Soft

Moult models are sensitive to trap-shyness



- Estimates are biased when non-moulting birds are easier to catch than moulting birds
- Moult scores from recaptured individuals can mitigate this bias

Conclusions

- Biometrics collected during ringing can complement demographic analyses by shedding light on annual cycle-phenology
- obtaining unbiased inferences can be challenging with real-world datasets
- We developed model extensions that greatly improve fits of "messy" real world datasets, especially when mark-recapture data are available
- HMC-based software implementation: https://github.com/pboesu/moultmcmc

Hanmer et al. (2022) Biology Letters; Boersch-Supan et al. (2022) arXiv:2205.12120; Boersch-Supan et al. (in press) Ostrich

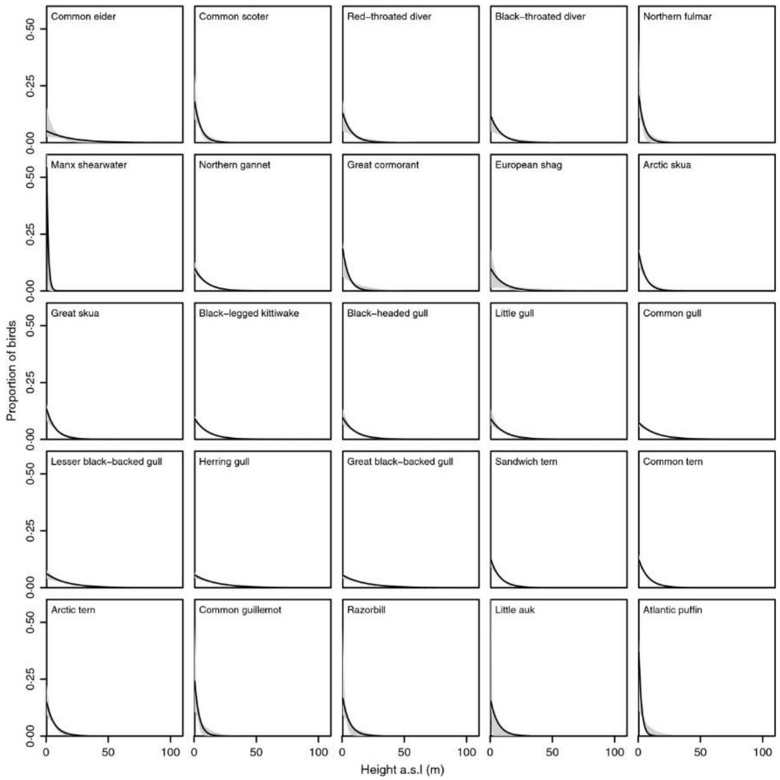
Case study 3:

How high do birds fly?

Seabird distributions

- Crucial to identify overlap with human infrastructure
- Accurately measuring seabird distributions at relevant spatial and temporal scales is not trivial
- Vertical distributions are dynamic on small/short spatio-temporal scales, making accurate measurement difficult
- Many monitoring approaches, very little validation, performance metrics of commercial tools generally unavailable

Human observers



Measurement:
Laser rangefinder accuracy $\pm$1m
Unaided human observers $\pm$ 10-20m

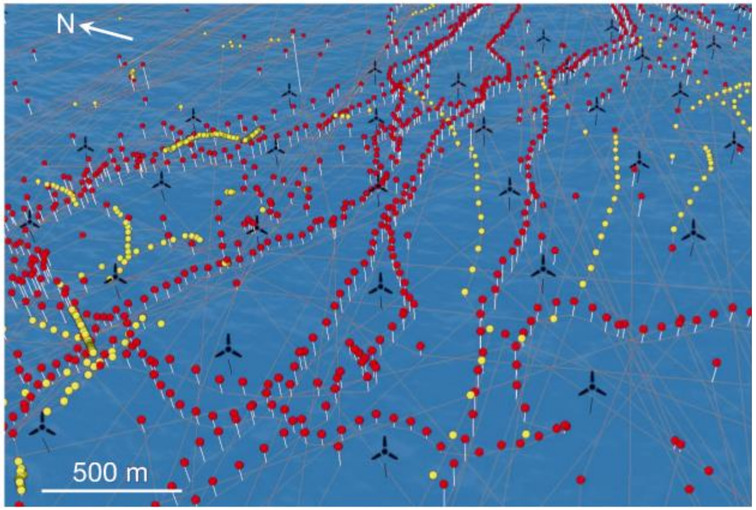
Cross comparisons between unaided human observers and Laser rangefinders show good agreement between both methods

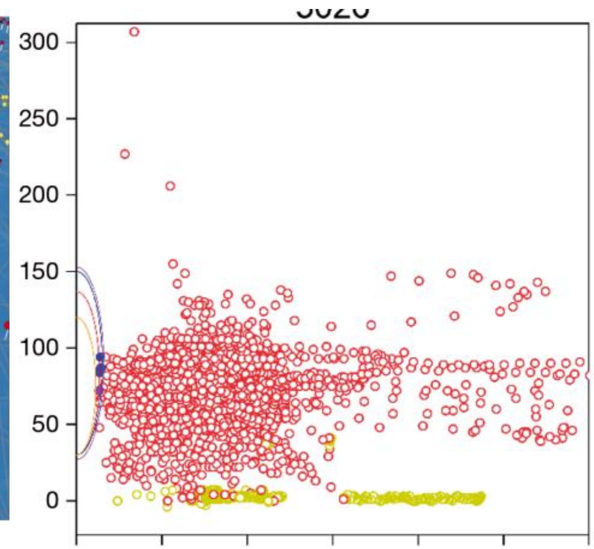
Sampling:
Decreasing detectability with horizontal range well established
Detectability impacts on 3D sampling biases poorly understood

By and large these form the evidence base for regulatory assessments in UK

Johnston et al 2013 J Appl Ecol

Animal-borne GPS altimetry





High-frequency GPS vertical accuracy ±5m

Sampling challenges:
short battery life -> small deployment scales
who/how many can we tag?

Thaxter et al. 2018 MEPS

Animal-borne GPS altimetry

Measurement:
Low-frequency GPS altitude is noisy!
Important to not take raw fixes face-value but account for measurement errors

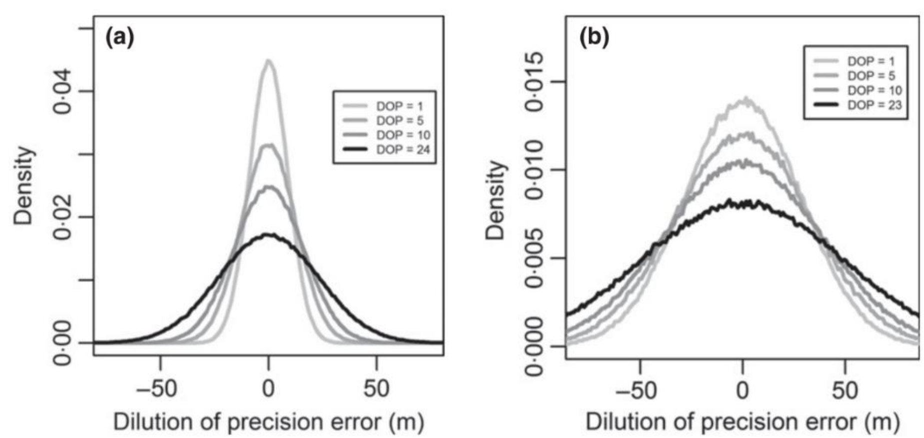
Measurement error magnitude (10-50m) estimated using state-space models

Sampling:
For all animal-borne methods sampling issues need to be considered

$$\log(\mathrm{alt}_{i,k,l}) \sim N(\mu_{i,k,l}, \sigma_k^2)$$

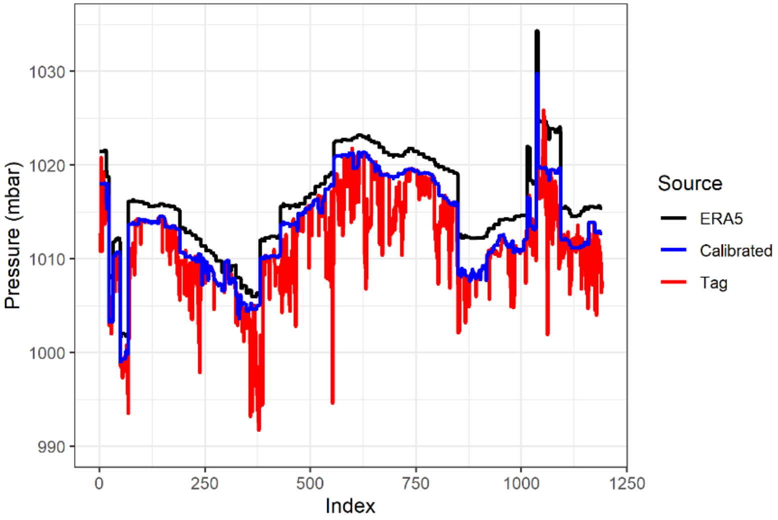
$$\mathrm{obs}_j \sim N(\mathrm{alt}_j, \sigma_j^2)$$

$$\sigma_j^2 = \rho + \omega \cdot \mathrm{DOP}_j$$



Ross-Smith et al. 2016 J Appl Ecol, Peron et al. 2020 Movement Ecol

Animal-borne barometric altimetry



$$P = P_b \exp\left[\frac{-g_0 M\,(h - h_b)}{R^* T_b}\right]$$

Measurement:
Absolute barometric measurements are very precise
But large uncertainty about sea surface air pressure leads to uncertainty/bias in heights
Uncertainty comes in part from scale mismatch of atmospheric models

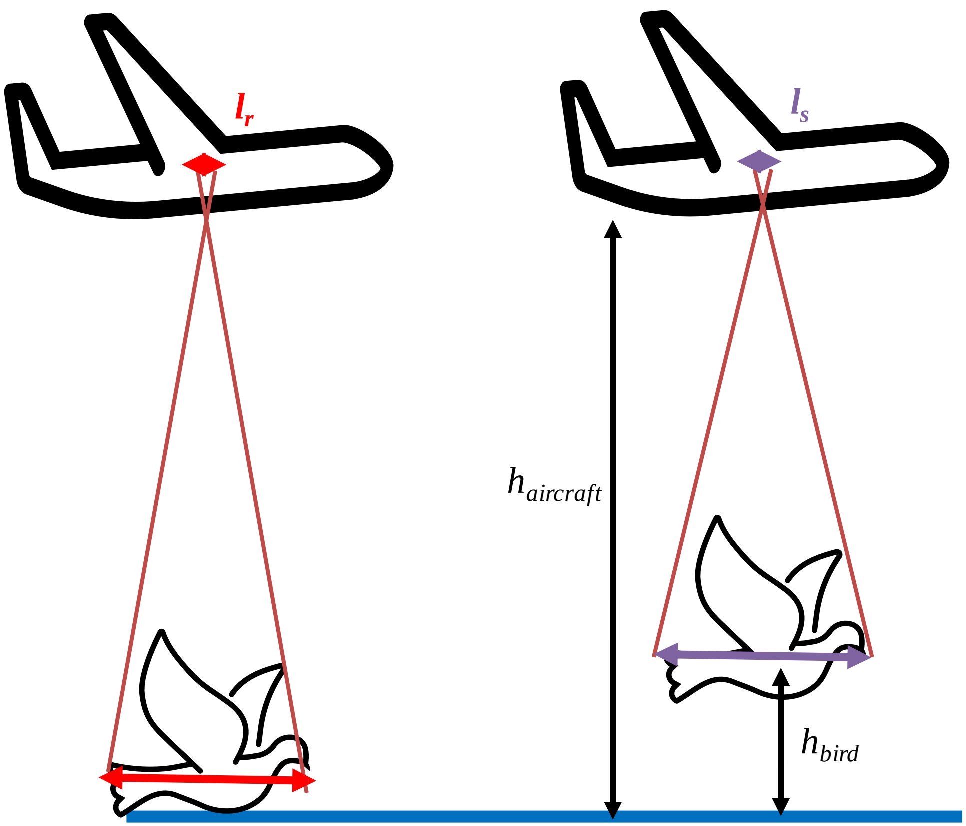
We use behavioural classification of horizontal movements to calibrate sea surface air pressure from floating birds,
but validation is not trivial

Sampling:
For all animal-borne methods sampling issues need to be considered

Johnston et al. (in press) Movement Ecology

Single-camera photogrammetry

Digital aerial surveys + manual species ID, semi-automatic apparent length measurements



Indirectly known from reference **distribution**

$$h_{bird} = h_{aircraft}\left(1 - \frac{l_r}{l_s}\right)$$

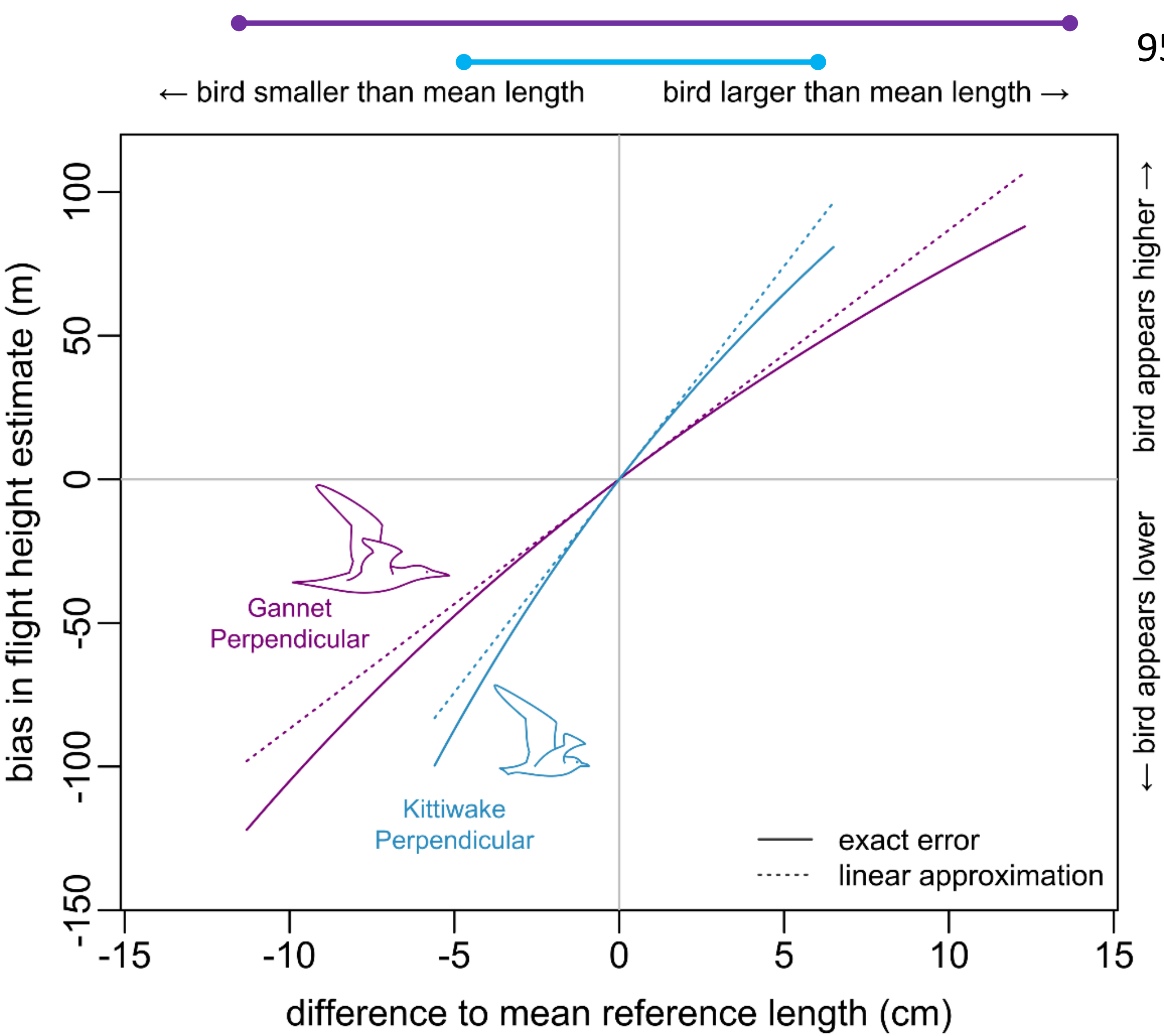
direct measurements (with error)

Symbol	Estd. error (95% CI)	Estd. error (CV%)
l_r	$\pm 12\text{cm}$	10%
l_s	$\pm 4\text{cm}$	3-5%
h_{bird}	?	
$h_{aircraft}$	$\pm 10 - 20\text{m}$	2-4%

Error analysis shows individual flight heights should have errors on the order of ±100m

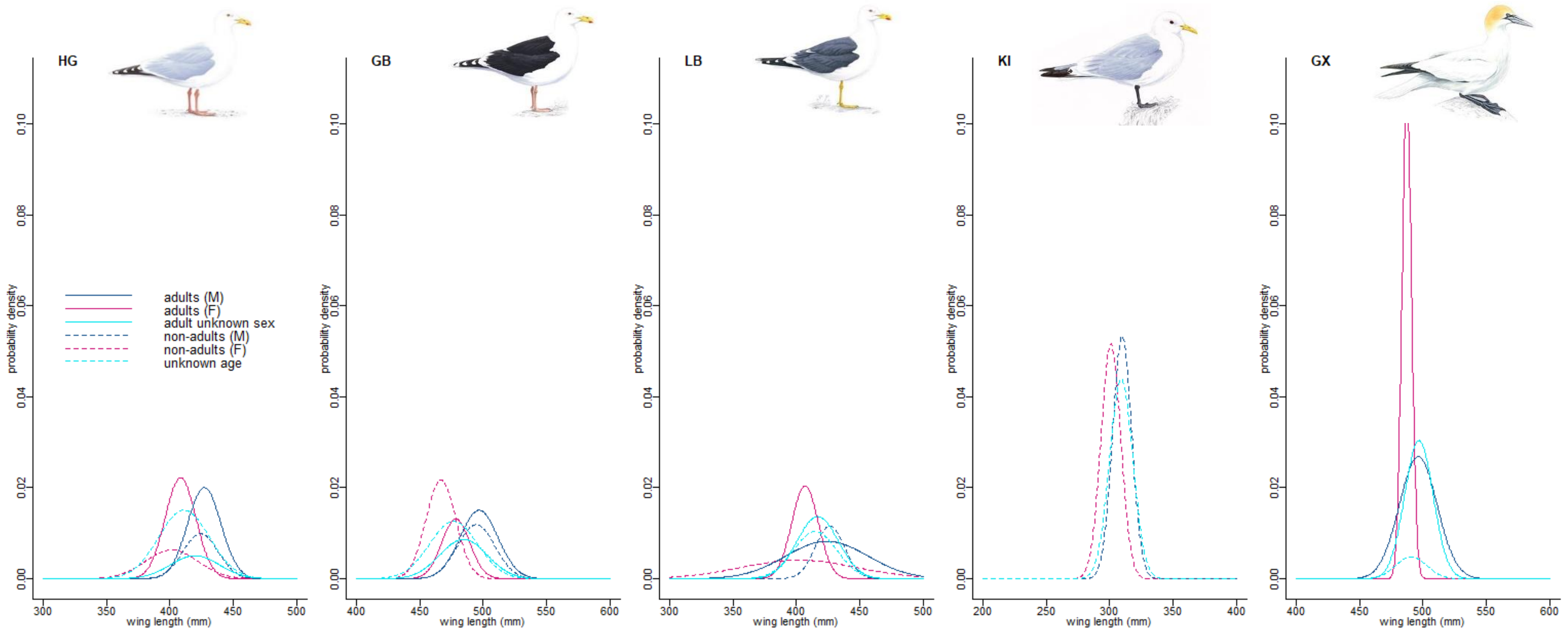
Humphries et al. 2023 Marine Biology, Boersch-Supan et al. (submitted)

Altitude error is dominated by body size



Boersch-Supan et al. (submitted)

The fundamental driver of this is natural size variation

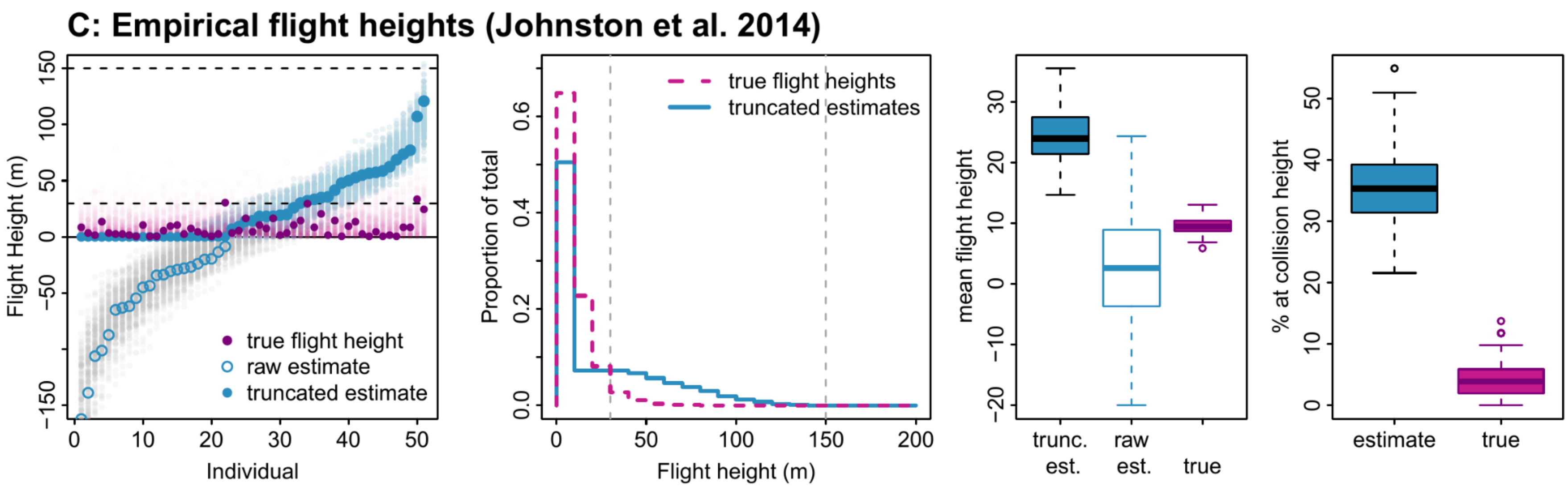


wing length (mm)

Wing length variation in adult seabirds is 1-7% (CV) within sexes, and 3-7% (CV) across sexes. Most species cannot be sexed from imagery .

Boersch-Supan et al. submitted

Single-camera photogrammetry



Measurement:
Large uncertainty about true body size → large height uncertainty

Inferred height distribution has biased mean, inflated tails → large bias in collision risk estimates

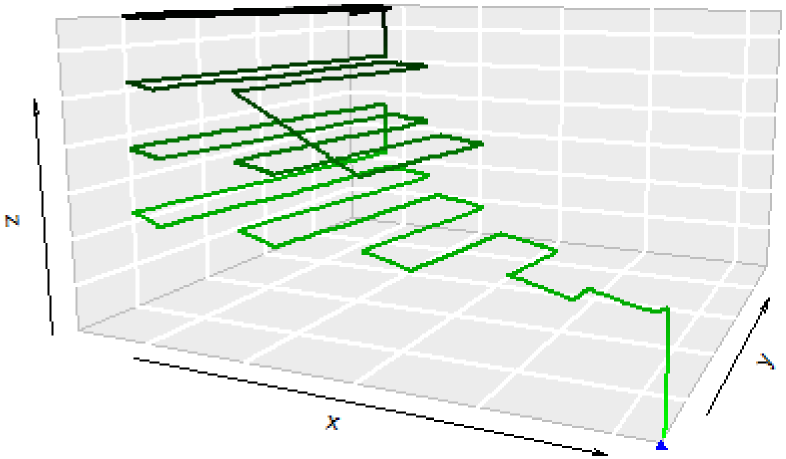
Sampling:
25-30% of birds not identifiable to species or in unsuitable flight posture

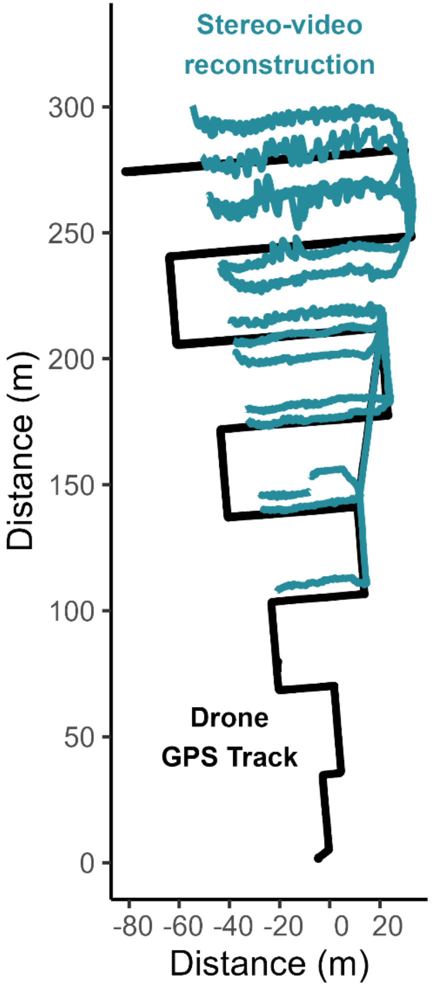
Boersch-Supan et al. (submitted)

Stereo-photogrammetry

Off-the-shelf HD surveillance cameras +
AI object detection/tracking/species ID
as a low cost scalable monitoring approach?

Drone trials



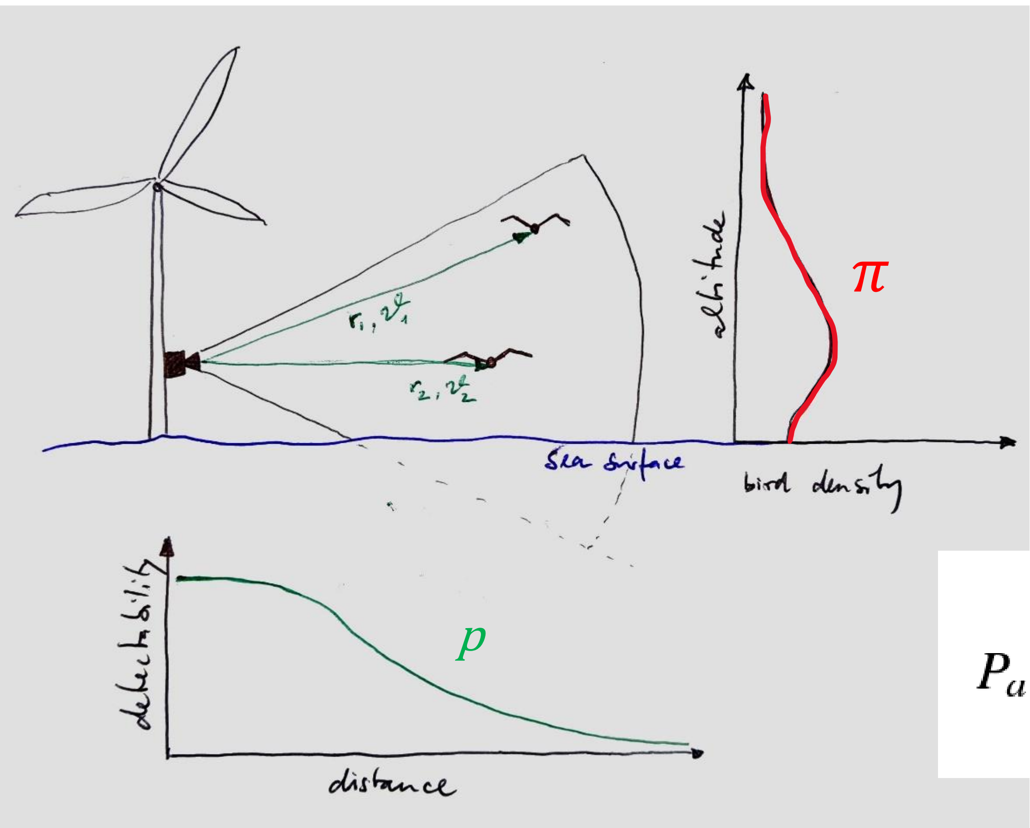


Initial results with a ground-biased calibration suggest position error ≤ 10% of range
Precision sensitive to frame rate (mismatch), image analysis calibration method

3D (Camera Trap) Distance Sampling

Sampling: Effective sampled volume depends on visibility (e.g. fog)

Idea:
jointly estimate detection function and flight height distribution using 3D distance sampling

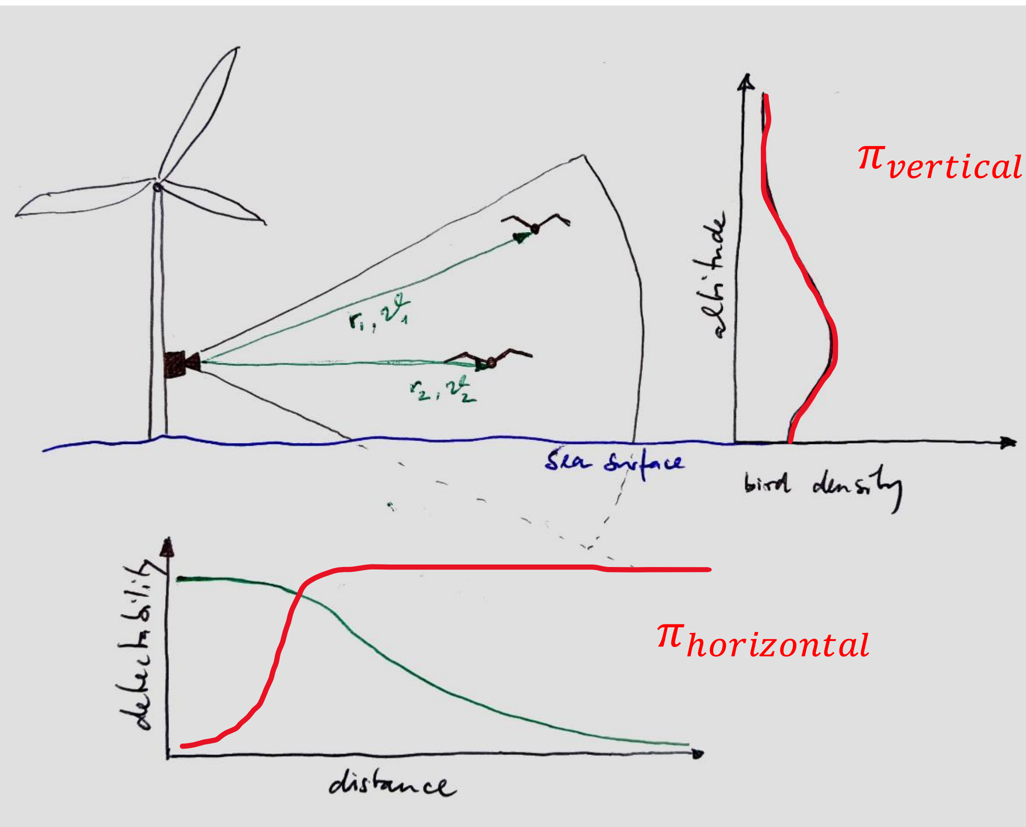


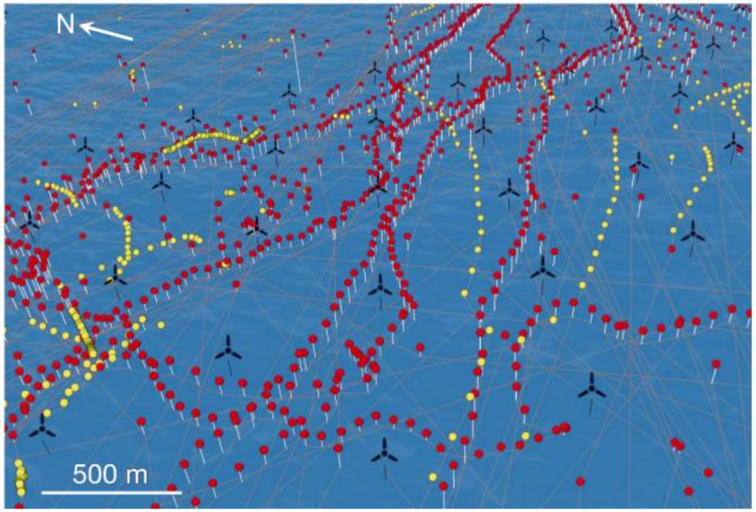
$$P_a = \int_0^{\gamma\pi} \int_0^{w} p(r,\theta)\, \pi_{r,\theta}(r,\theta)\, \mathrm{d}r\, \mathrm{d}\theta.$$

Cox et al. 2011 JRSS C Appl Stat

Added challenges

- (Most) Birds actively avoid turbines (=detector locations)
- Measurement errors in r,θ





Cox et al. 2011 JRSS C Appl Stat

Flight heights conclusion

- Flight heights remain difficult to characterize
- Much more rigorous assessments of uncertainty and their impact on collision risk estimates are needed
- Even when measurement and sampling errors are known, inferences may be hard to obtain because errors are large w.r.t inference scale

General Conclusions

- Thanks to an enormous volunteer effort bird populations in the UK are among the best monitored globally
- Wildlife population assessment in practice involves balancing optimal survey designs and statistical frameworks with limited resources (volunteer/analyst time, software, hardware)
- Careful modelling is necessary to account for observation process
- Rich datasets can be a technical challenge, but they provide exciting opportunities for methodological developments

Answer our open questions!

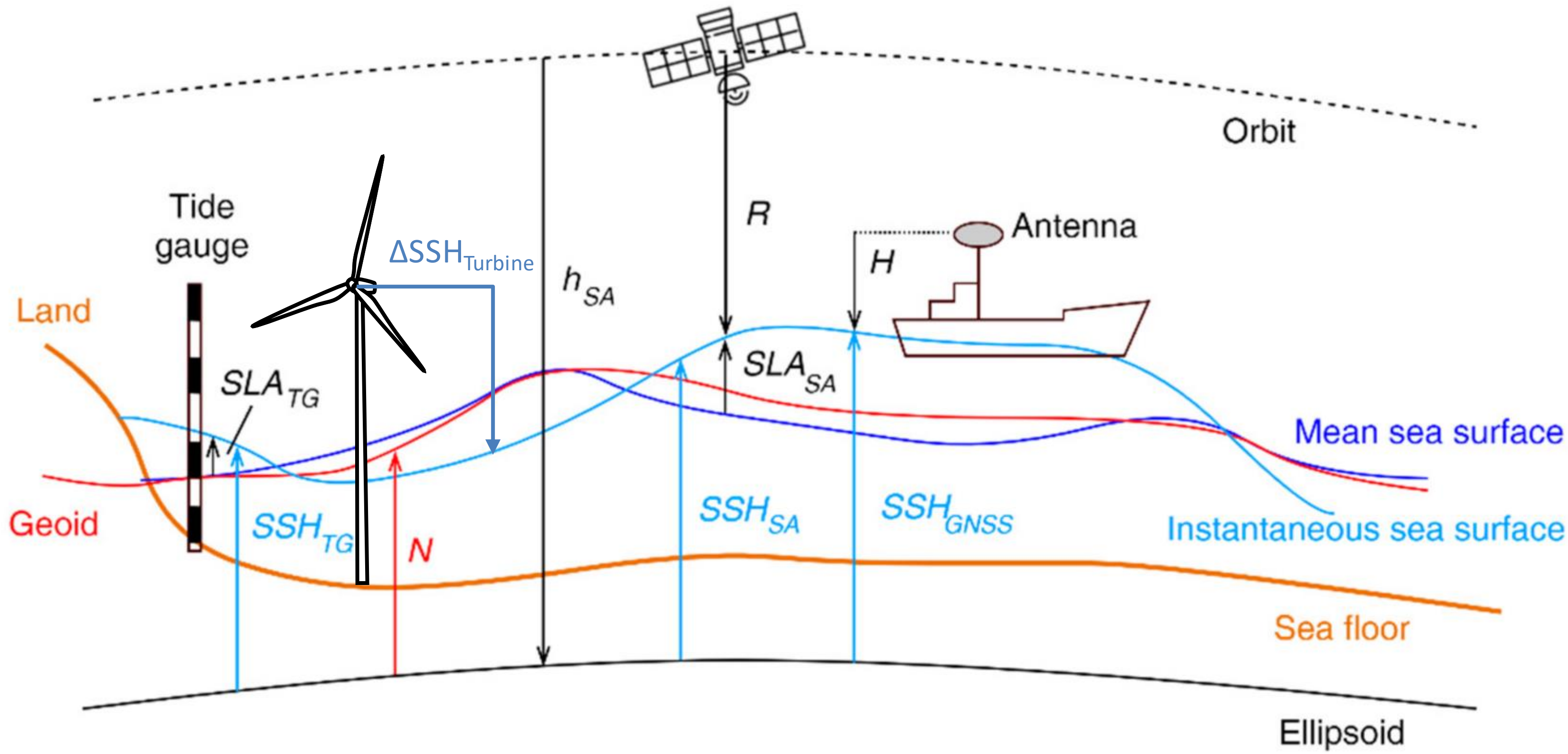
- Mark-recapture models with transient individuals
- Heterogeneity in recovery/reporting rates in dead recovery models
- Continuous-time mark-recapture for colour-ring resighting data
- Spatio-temporal models for range expansion / contraction
- Spatio-temporal models for avian disease outbreaks
- Abundance models for acoustic data
- Misclassification errors for acoustic data
- Count regression models for highly over/underdispersed data
- Citizen science sampling biases
- …

Tipling / BTO

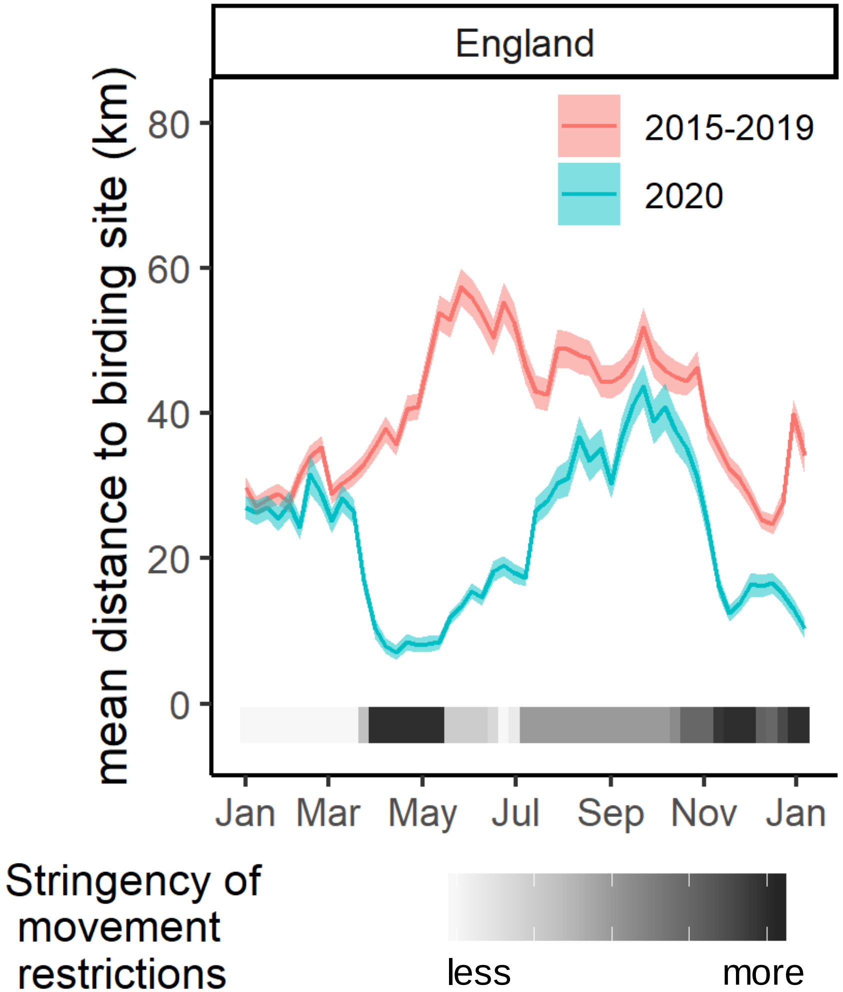
ACKNOWLEDGEMENTS

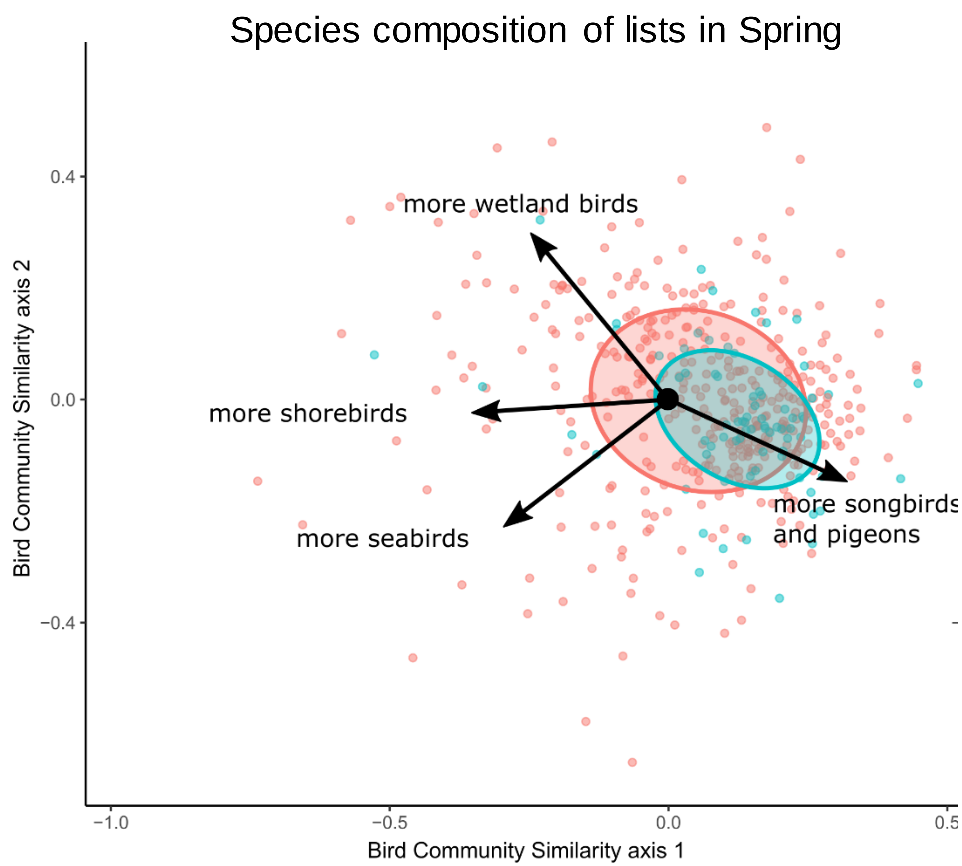
Bird monitoring in the UK is only possible because of the dedication of **thousands of volunteers** and the financial support from **survey partners** and from **charitable contributions to the BTO**.

Added challenge: What's the frame of reference?



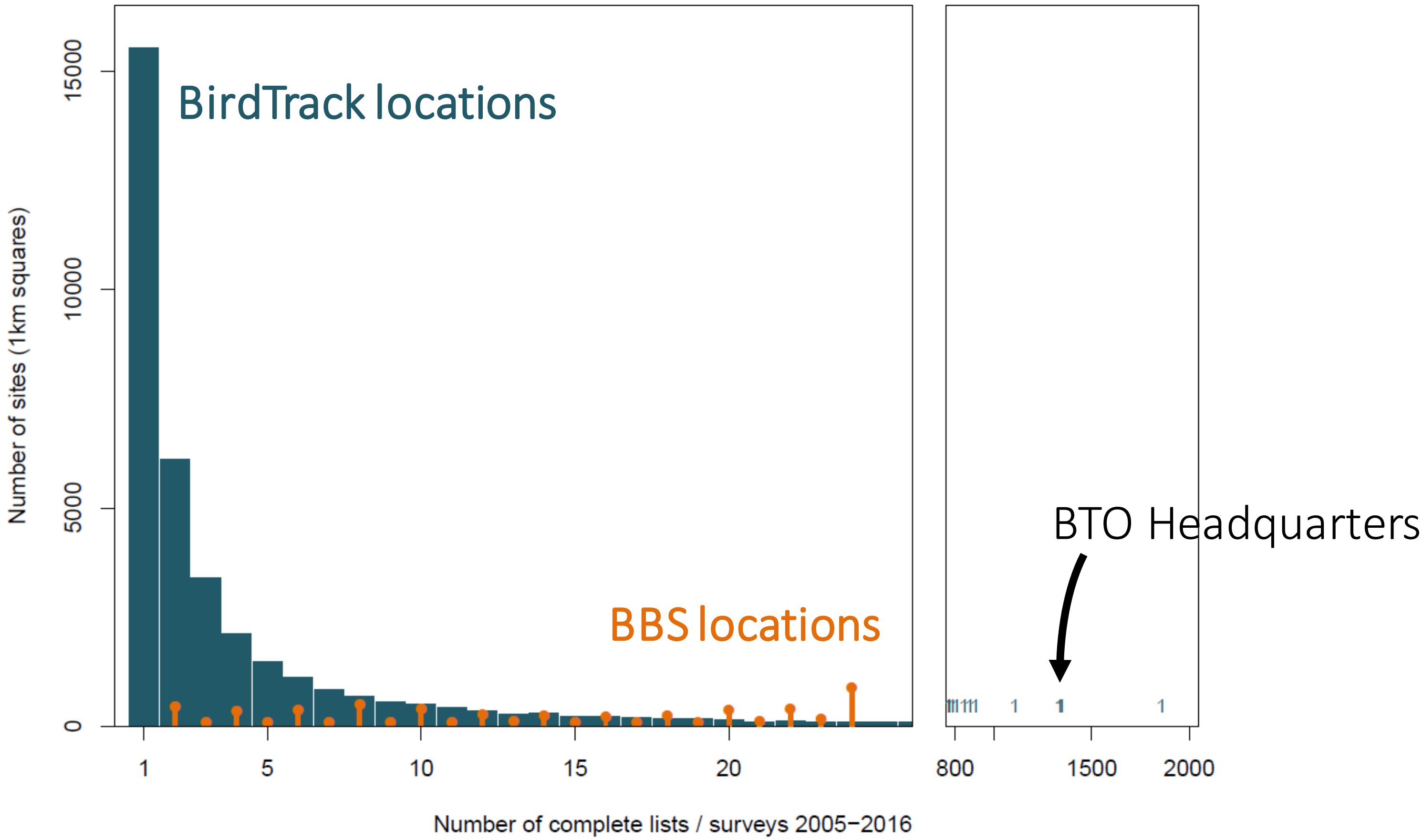
Site selection bias under COVID-19





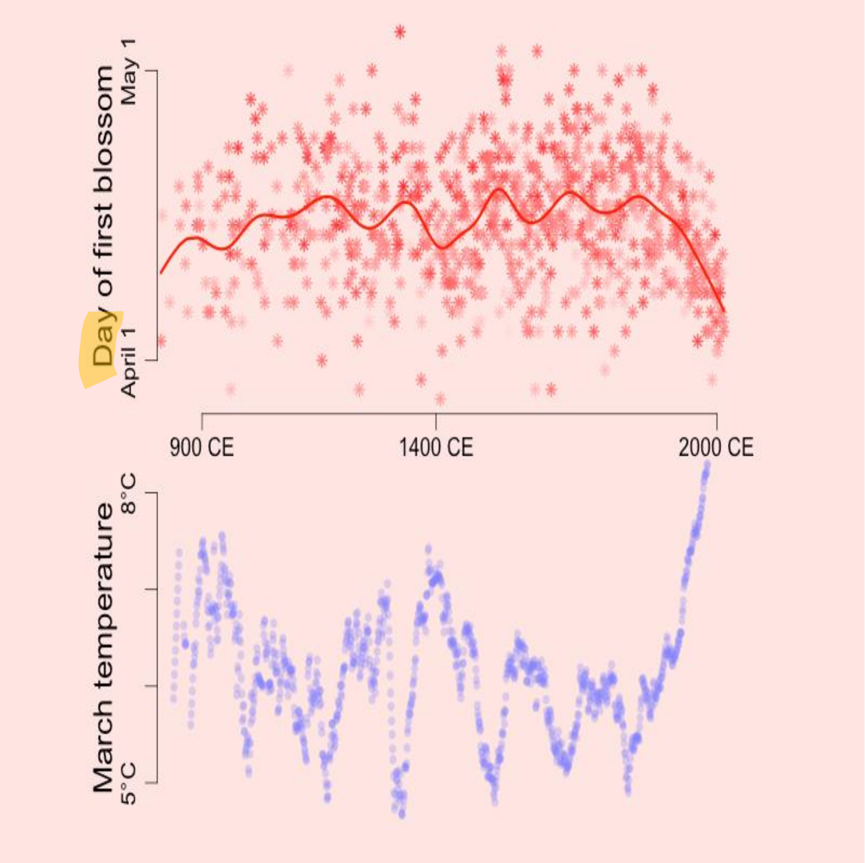
? Most BirdTrack sites are one-offs

Most BirdTrack sites are rarely revisited, a few **very** often
i.e. effective sample size << nominal sample size

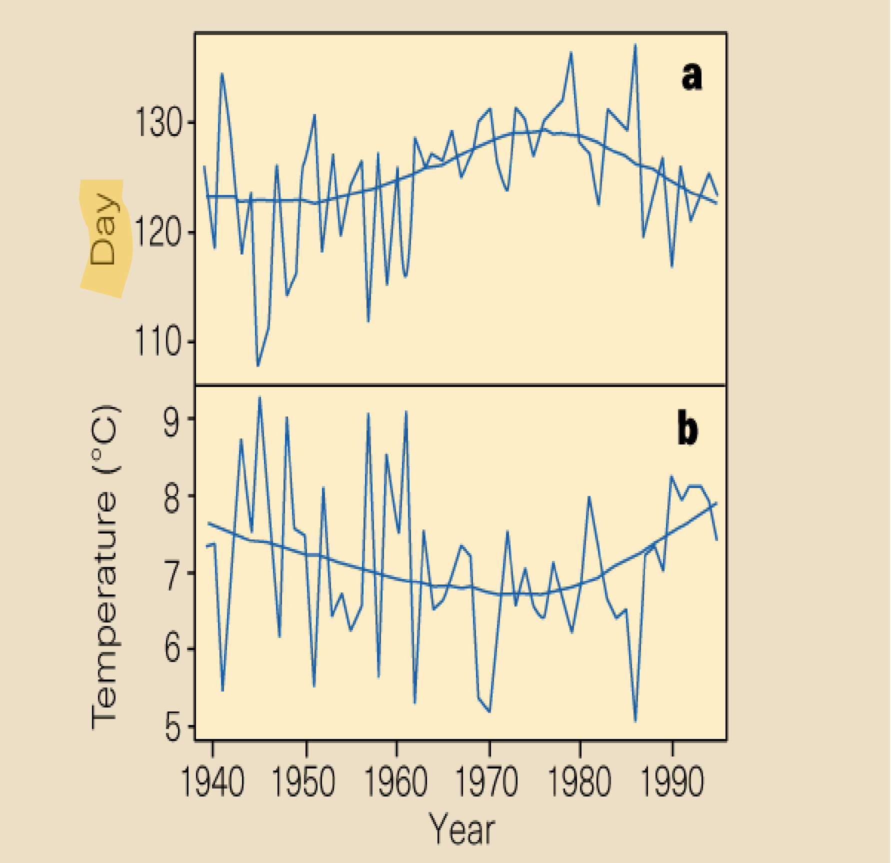


Phenology can provide insight into ecosystem processes

Japanese cherry blossom



Chaffinch egg laying



Aono & Saito (2010) Int J Biometeorol; Crick & Sparks (1999) Nature

Conclusions

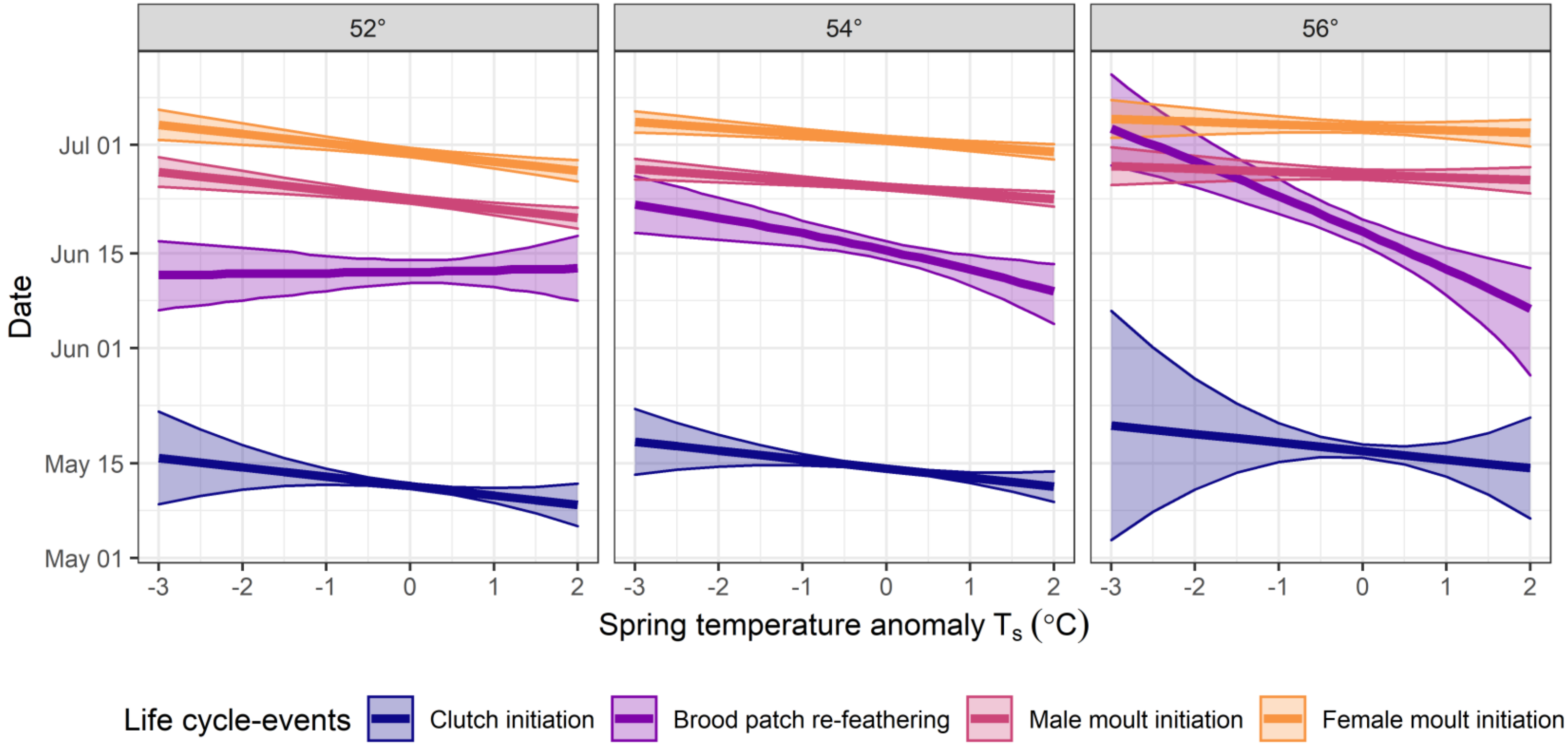
- Biometrics collected during ringing can complement demographic analyses by shedding light on annual cycle-phenology, but obtaining unbiased inferences can be challenging with real-world datasets
- We developed model extensions that greatly improve fits of "messy" real world datasets, especially when mark-recapture data are available

- Extended moult models are implemented in R package **moultmcmc**
  - Bayesian inference using HMC via Stan
  - interface for random effects in linear predictors on μ, σ, τ in work
  - Circular model variants in work to fully relax linear time-assumption

Software: https://github.com/pboesu/moultmcmc
Methods paper: https://arxiv.org/abs/2205.12120

Erni et al. (2013) J Stat Soft, Boersch-Supan et al. (2022) arXiv:2205.12120

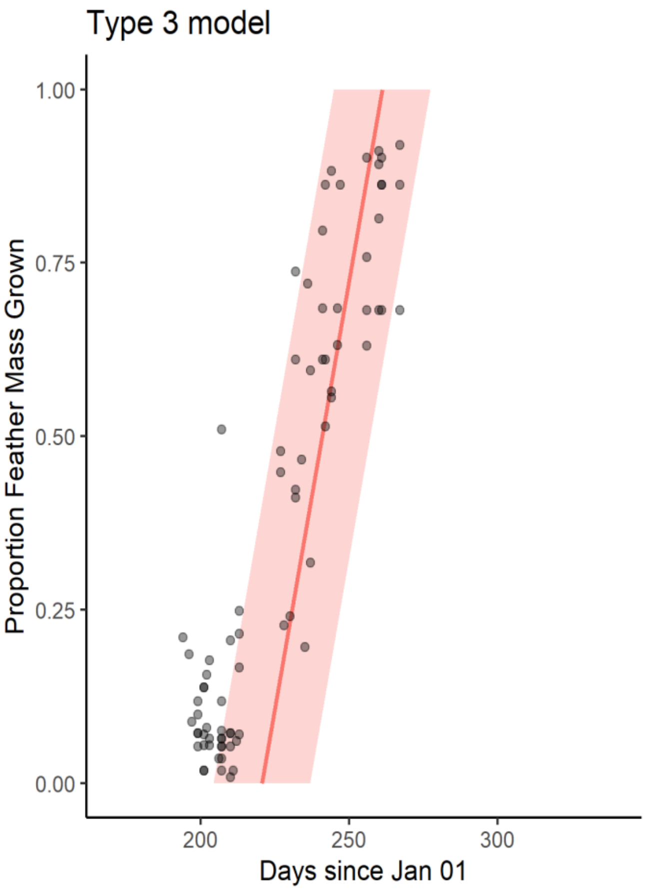
Other mechanistic insights

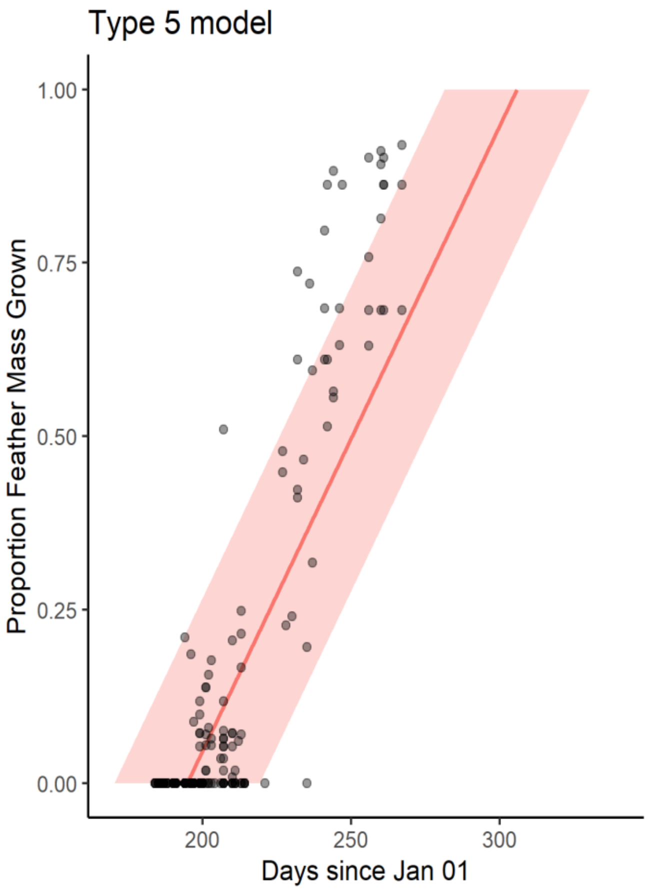


- Timing of end of breeding differs most between regions, identifying a potential pinchpoint in the annual cycle.

Hanmer et al. 2022 Biol Letters

Eurasian siskins – Poor fit of moult models

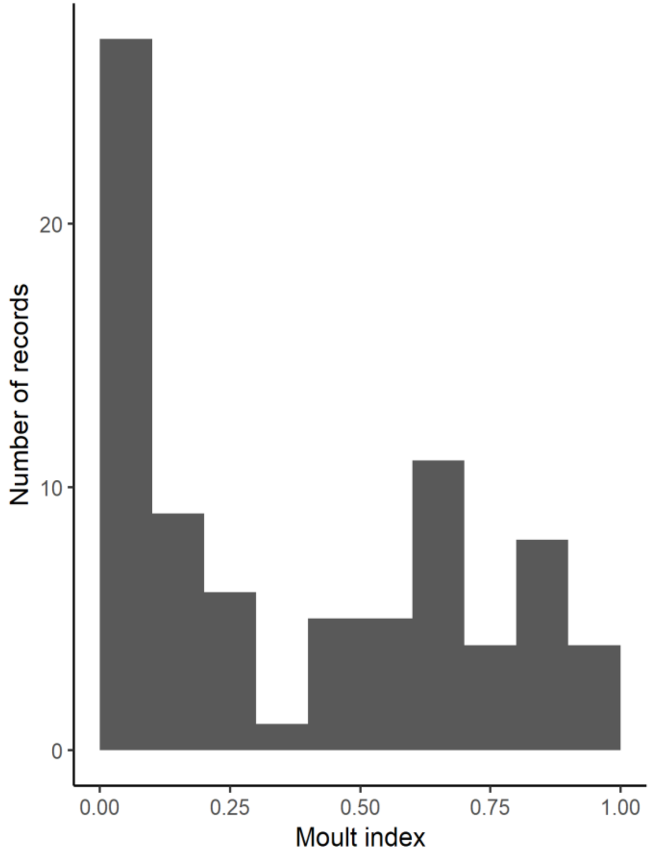


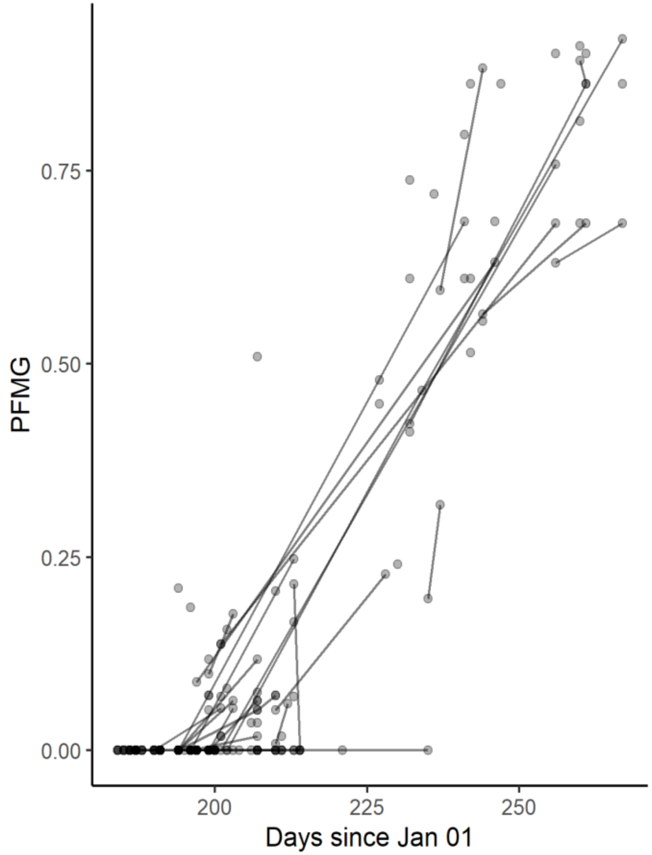


Moult models are a special case of interval-censored regression models (tobit-like)

Boersch-Supan et al. (2022) arXiv:2205.12120

Dataset violates assumption of homogeneous capture probabilities.
Early moult stages are over-represented, ***but there are known recaptures!***





Boersch-Supan et al. (2022) arXiv:2205.12120