Survey design in occupancy studies

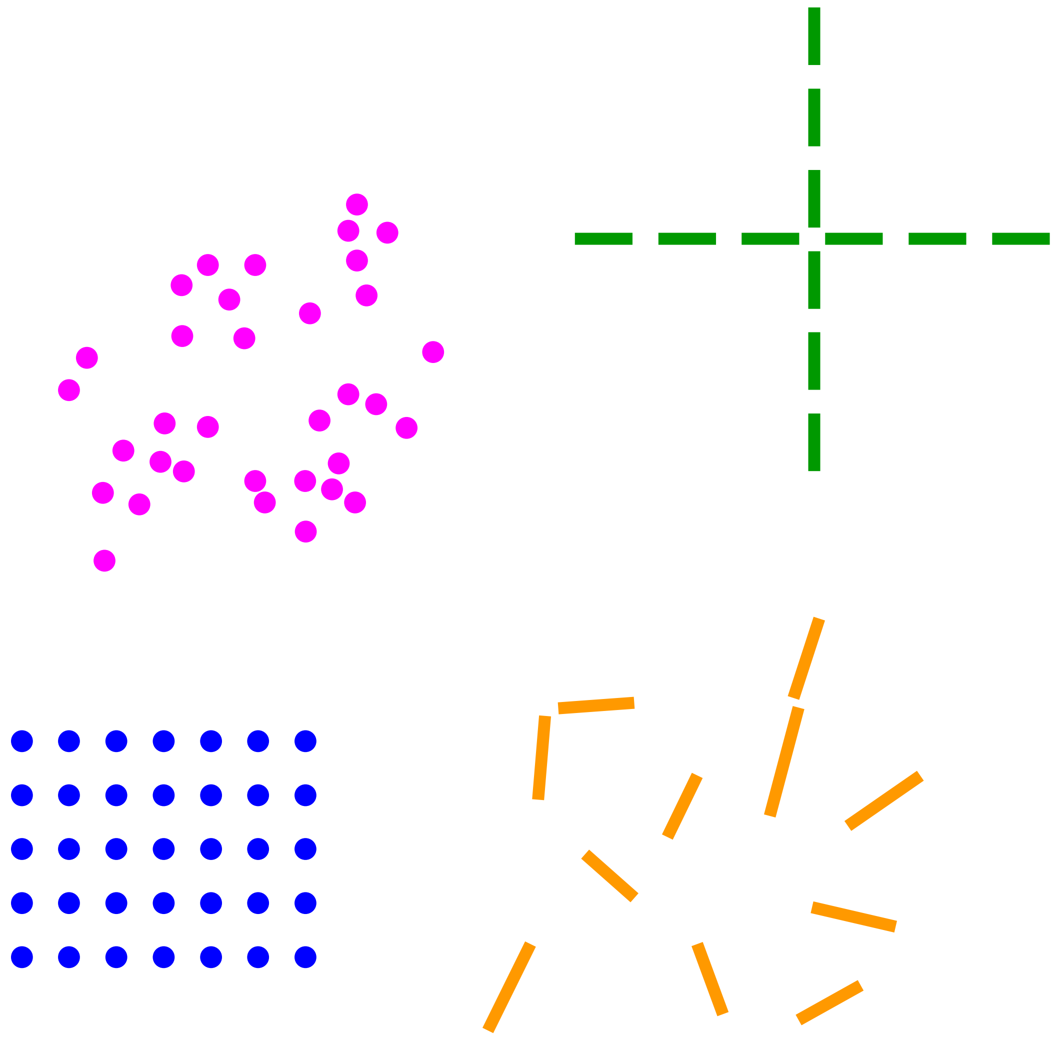
Gesa von Hirschheydt

25 June 2024

Standard sampling design

- *J* sites with *K* visits each

	True state	Visit 1	Visit 2	Visit 3	Visit 4	Visit 5
Site 1	1	1	0	0	1	0
Site 2	0	0	0	0	0	0
Site 3	1	0	0	1	1	0
Site 4	1	0	0	0	0	0
Site 5	1	0	1	0	0	1
Site 6	0	0	0	0	0	0
Site 7	0	0	0	0	0	0
Site 8	1	0	0	0	0	1



MacKenzie et al. (2002) *Ecology*
Tyre et al. (2003) *Ecological Applications*

Standard sampling design

- *J* sites with *K* visits each → how to define *J* and *K*?

Do you want to…

… estimate occupancy with a certain degree of precision?

… compare occupancy between two habitats or points in time?

… evaluate the detection probability of a new sampling method?

… compare co-occurrence patterns of a predator-prey pair?

… estimate local population dynamics?

Standard sampling design

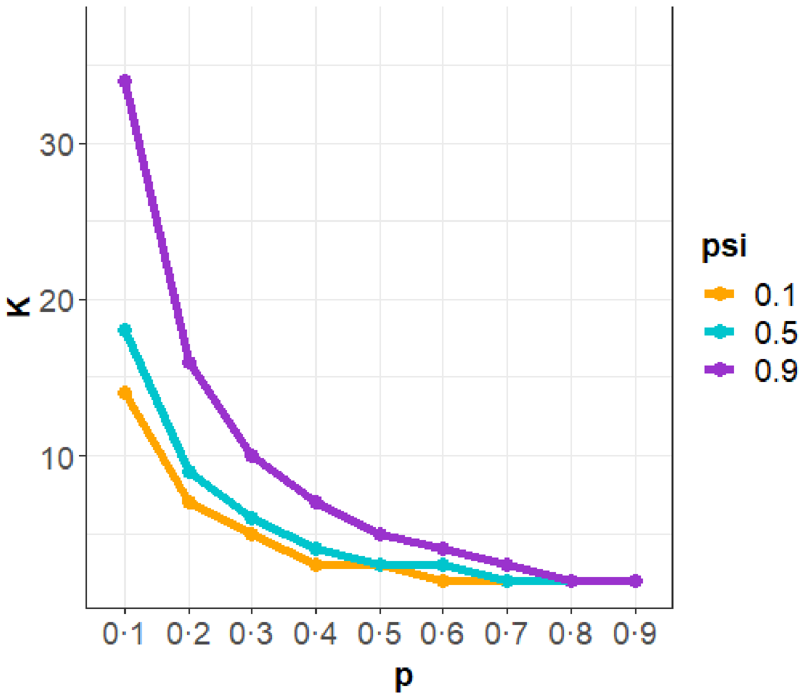
- *J* sites with *K* visits each → how to define *J* and *K*?

Goal: estimate occupancy with a certain degree of precision

$$\operatorname{var}(\hat{\psi}) = \frac{\psi K}{TS}\left[(1-\psi) + \frac{(1-p^*)}{p^* - Kp(1-p)^{K-1}}\right]$$

Ψ	*psi* = occupancy probability
K	number of repeated visits
TS	total number of conducted surveys (*J*K*)
p	detection probability
*p**	cumulative detection probability = $1-(1-p)^K$

→ define *TS, psi, p*
→ optimize for *K*



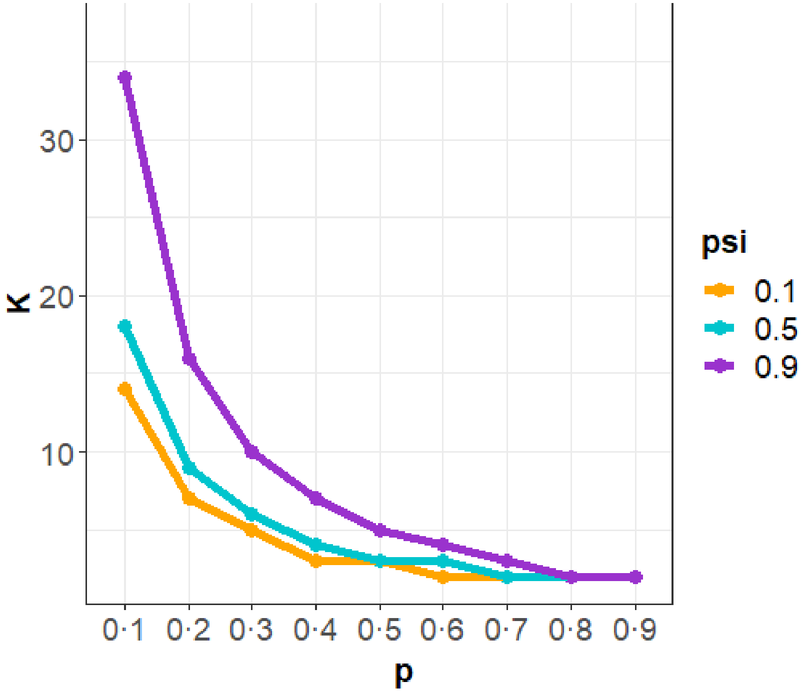
MacKenzie & Royle (2005) *Journal of Applied Ecology*

Standard sampling design

- *J* sites with *K* visits each → how to define *J* and *K*?

Conclusions

- low detectability → fewer sites with more visits
- low occupancy → more sites with fewer visits



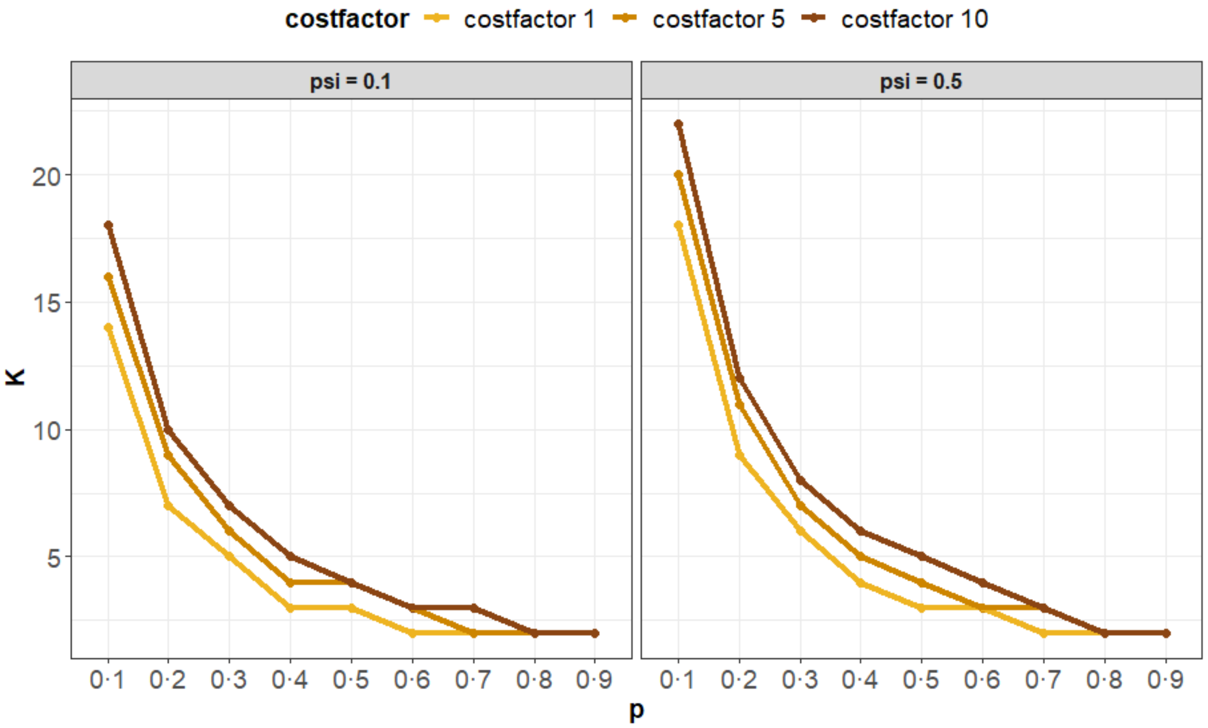
MacKenzie & Royle (2005) *Journal of Applied Ecology*

Standard sampling design

- *J* sites with *K* visits each → how to define *J* and *K*?

Conclusions

- low detectability → fewer sites with more visits
- low occupancy → more sites with fewer visits
- when new sites are more costly



MacKenzie & Royle (2005) *Journal of Applied Ecology*

Standard sampling design

- *J* sites with *K* visits each → how to define *J* and *K*?

Conclusions

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- low occupancy → more sites with fewer visits
- when new sites are more costly → fewer sites with more visits

MacKenzie & Royle (2005) *Journal of Applied Ecology*

Standard sampling design

- *J* sites with *K* visits each → how to define *J* and *K*?

Conclusions

- low detectability → fewer sites with more visits
- low occupancy → more sites with fewer visits
- when new sites are more costly → fewer sites with more visits

- if detectability is of key interest → fewer sites with more visits
- for most situations, *K* should ideally be ≥ 3
- if a design has to meet the objectives of several species, it is generally the design of the rarer & more difficult-to-detect species that works better for all

MacKenzie & Royle (2005) *Journal of Applied Ecology*
Field et al. (2005) *The Journal of Wildlife Management*
Guillera-Arroita et al. (2010) *Methods in Ecology and Evolution*

Different sampling designs

Standard design

- visit J sites K times each

Removal design

- visit J sites until first detection or up to K times

Conditional design

- visit J sites once, then resurvey sites with a detection an additional K-1 times

"Mixed design"

- visit J_S sites once, J_R sites K times

Any mixture of the above

True state
1
1
1
1
0

Standard

1	2	3	4	5
1	0	1	1	0
0	0	0	0	0
0	0	1	1	0
0	0	0	0	1
0	0	0	0	0

Removal

1	2	3	4	5
1				
0	0	0	0	0
0	0	1		
0	0	0	0	1
0	0	0	0	0

Conditional

1	2	3	4	5
1	0	1	1	0
0				
0				
0				
0				

Specht et al. (2017) *Methods in Ecology and Evolution*

Removal sampling design

- visit *J* sites until first detection or up to *K* times

Removal

1	**2**	**3**	**4**	**5**
1				
0	0	0	0	0
0	0	1		
0	0	0	0	1
0	0	0	0	0

MacKenzie & Royle (2005) *Journal of Applied Ecology*

Removal sampling design

- visit *J* sites until first detection or up to *K* times

Ratio of standard errors for standard vs. removal designs.

Colours indicate whether removal design (orange) or standard design (blue) yield higher precision.

p	ψ								
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
0.1	0.9	0.94	0.98	1.04	1.1	1.18	1.3	1.46	1.74
0.2	0.91	0.94	0.99	1.04	1.1	1.18	1.28	1.44	1.71
0.3	0.92	0.95	0.99	1.04	1.1	1.17	1.27	1.42	1.68
0.4	0.93	0.96	0.99	1.03	1.09	1.17	1.26	1.4	1.64
0.5	0.93	0.96	1	1.04	1.08	1.16	1.24	1.37	1.6
0.6	0.94	0.97	1.01	1.06	1.09	1.15	1.22	1.35	1.55
0.7	0.95	0.96	0.97	1.01	1.07	1.13	1.22	1.31	1.48
0.8	1	1.02	1.04	1.07	1.09	1.11	1.15	1.25	1.45
0.9	1.02	1.05	1.07	1.1	1.13	1.17	1.2	1.24	1.31

Conclusion

Removal design is more efficient than standard design for any species with *psi* ≥ 0.4.

MacKenzie & Royle (2005) *Journal of Applied Ecology*

Conditional sampling design

- visit *J* sites until first detection or up to *K* times

Conditional

1	2	3	4	5
1	0	1	1	0
0				
0				
0				
0				

Specht et al. (2017) *Methods in Ecology and Evolution*

Conditional sampling design

$RMSE(\hat{\psi})$

p \ ψ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	.000	.002	.002	.004	.009	.012	.024	.025	.029
0.2	.013	.008	.005	.011	.017	.006	.003	.013	.021
0.3	.024	.007	.003	.016	.017	.004	.004	.013	.010
0.4	.036	.012	.004	.015	.004	.008	.013	.021	.019
0.5	.037	.015	.000	.009	.004	.014	.015	.024	.029
0.6	.045	.023	.010	.005	.015	.020	.023	.032	.033
0.7	.045	.024	.011	.005	.015	.021	.029	.040	.039
0.8	.045	.032	.017	.000	.015	.027	.037	.040	.046
0.9	.045	.035	.019	.006	.011	.023	.029	.035	.046

$SE(\hat{\psi})$

p \ ψ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	.012	.005	.004	.008	.022	.038	.055	.070	.078
0.2	.008	.003	.002	.006	.015	.026	.037	.047	.052
0.3	.006	.002	.002	.005	.012	.020	.028	.036	.040
0.4	.006	.001	.001	.003	.010	.016	.023	.029	.033
0.5	.005	.001	.000	.003	.007	.014	.019	.024	.027
0.6	.004	.000	.001	.005	.007	.011	.015	.020	.022
0.7	.003	.000	.002	.001	.005	.009	.013	.016	.018
0.8	.004	.001	.003	.004	.006	.007	.008	.012	.015
0.9	.006	.005	.001	.006	.008	.009	.010	.010	.010

$RMSE(\hat{p})$

p \ ψ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	.067	.050	.026	.024	.020	.007	.008	.008	.008
0.2	.056	.029	.027	.013	.007	.008	.000	.000	.010
0.3	.039	.028	.027	.013	.007	.008	.000	.000	.000
0.4	.047	.032	.023	.013	.014	.016	.008	.000	.000
0.5	.050	.035	.024	.013	.007	.008	.000	.000	.000
0.6	.059	.041	.019	.014	.008	.008	.000	.000	.000
0.7	.072	.043	.014	.008	.000	.000	.000	.000	.000
0.8	.090	.037	.023	.008	.000	.000	.000	.000	.000
0.9	.118	.050	.019	.013	.013	.000	.000	.000	.000

$SE(\hat{p})$

p \ ψ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	.061	.031	.019	.010	.005	.001	.003	.006	.003
0.2	.080	.043	.022	.014	.007	.000	.003	.009	.004
0.3	.085	.043	.026	.020	.005	.002	.003	.007	.003
0.4	.109	.045	.027	.013	.008	.001	.003	.008	.003
0.5	.089	.040	.028	.021	.006	.003	.007	.009	.001
0.6	.102	.066	.038	.029	.003	.000	.002	.004	.003
0.7	.080	.038	.027	.020	.002	.003	.010	.006	.000
0.8	.043	.002	.001	.003	.005	.006	.002	.001	.003
0.9	.000	.002	.004	.005	.006	.007	.007	.004	.001

A-optimality (RMSE)

p \ ψ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	.067	.048	.024	.020	.011	.004	.004	.015	.016
0.2	.069	.037	.022	.002	.010	.010	.012	.027	.037
0.3	.063	.035	.024	.024	.003	.016	.019	.036	.009
0.4	.083	.044	.019	.019	.002	.004	.026	.013	.010
0.5	.087	.050	.024	.000	.000	.013	.028	.001	.010
0.6	.105	.063	.029	.014	.014	.000	.017	.016	.014
0.7	.117	.067	.025	.018	.018	.005	.007	.022	.029
0.8	.134	.068	.050	.024	.024	.005	.018	.030	.033
0.9	.163	.090	.048	.034	.028	.028	.006	.022	.046

Standard Removal Conditional

A-optimality (SE)

p \ ψ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	.073	.026	.011	.030	.007	.016	.038	.058	.072
0.2	.088	.040	.003	.025	.023	.003	.015	.032	.044
0.3	.091	.041	.012	.009	.031	.010	.005	.021	.032
0.4	.115	.044	.016	.010	.027	.018	.000	.013	.024
0.5	.094	.039	.020	.003	.022	.007	.004	.012	.021
0.6	.105	.066	.033	.018	.018	.013	.003	.012	.017
0.7	.083	.038	.022	.009	.012	.003	.005	.007	.015
0.8	.048	.004	.002	.009	.015	.015	.002	.009	.018
0.9	.007	.005	.001	.003	.006	.002	.002	.004	.009

Standard Removal Conditional

Specht et al. (2017) *Methods in Ecology and Evolution*

Conditional sampling design

RMSE($\hat{\psi}$)

p \ ψ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	.000	.002	.002	.004	.009	.012	.024	.025	.029
0.2	.013	.008	.005	.011	.017	.006	.003	.013	.021
0.3	.024	.007	.003	.016	.017	.004	.004	.013	.010
0.4	.036	.012	.004	.015	.004	.008	.013	.021	.019
0.5	.037	.015	.000	.009	.004	.014	.015	.024	.029
0.6	.045	.023	.010	.005	.015	.020	.023	.032	.033
0.7	.045	.024	.011	.005	.015	.021	.029	.040	.039
0.8	.045	.032	.017	.000	.015	.027	.037	.040	.046
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SE($\hat{\psi}$)

p \ ψ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	.012	.005	.004	.008	.022	.038	.055	.070	.078
0.2	.008	.003	.002	.006	.015	.026	.037	.047	.052
0.3	.006	.002	.002	.005	.012	.020	.028	.036	.040
0.4	.006	.001	.001	.003	.010	.016	.023	.029	.033
0.5	.005	.001	.000	.003	.007	.014	.019	.024	.027
0.6	.004	.000	.001	.005	.007	.011	.015	.020	.022
0.7	.003	.000	.002	.001	.005	.009	.013	.016	.018
0.8	.004	.001	.003	.004	.006	.007	.008	.012	.015
0.9	.006	.005	.001	.006	.008	.009	.010	.010	.010

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0.3	.039	.028	.027	.013	.007	.008	.000	.000	.000
0.4	.047	.032	.023	.013	.014	.016	.008	.000	.000
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0.7	.072	.043	.014	.008	.000	.000	.000	.000	.000
0.8	.090	.037	.023	.008	.000	.000	.000	.000	.000
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0.5	.089	.040	.028	.021	.006	.003	.007	.009	.001
0.6	.102	.066	.038	.029	.003	.000	.002	.004	.003
0.7	.080	.038	.027	.020	.002	.003	.010	.006	.000
0.8	.043	.002	.001	.003	.005	.006	.002	.001	.003
0.9	.000	.002	.004	.005	.006	.007	.007	.004	.001

A-optimality (RMSE)

p \ ψ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
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0.4	.083	.044	.019	.019	.002	.004	.026	.013	.010
0.5	.087	.050	.024	.000	.000	.013	.028	.001	.010
0.6	.105	.063	.029	.014	.014	.000	.017	.016	.014
0.7	.117	.067	.025	.018	.018	.005	.007	.022	.029
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Standard Removal Conditional

A-optimality (SE)

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0.1	.073	.026	.011	.030	.007	.016	.038	.058	.072
0.2	.088	.040	.003	.025	.023	.003	.015	.032	.044
0.3	.091	.041	.012	.009	.031	.010	.005	.021	.032
0.4	.115	.044	.016	.010	.027	.018	.000	.013	.024
0.5	.094	.039	.020	.003	.022	.007	.004	.012	.021
0.6	.105	.066	.033	.018	.018	.013	.003	.012	.017
0.7	.083	.038	.022	.009	.012	.003	.005	.007	.015
0.8	.048	.004	.002	.009	.015	.015	.002	.009	.018
0.9	.007	.005	.001	.003	.006	.002	.002	.004	.009

Standard Removal Conditional

	ψ								
p	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
0.1	C	S	S	R	R	R	R	R	R
0.2	C	S	S	R	R	R	R	R	R
0.3	C	S	S	R	R	R	R	R	R
0.4	C	S	R/S	R	R	R	R	R	R
0.5	C	S	R/S	R	R	R	R	R	R
0.6	C	C/S	R/S	R	R	R	R	R	R
0.7	C	C/S	S	R/S	R	R	R	R	R
0.8	C	C	R	R	R	R	R	R	R
0.9	C	C	C	R	R	R	R	R	R

Specht et al. (2017) *Methods in Ecology and Evolution*
Reich (2020) *Biometrics*

Conditional sampling design

Conclusions

- Conditional design is most efficient for rare species
- Standard design is most efficient for intermediate-occupancy species
- Standard design was generally the next-best performing model
- Removal design is most efficient when species is common

	ψ								
p	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
0.1	C	S	S	R	R	R	R	R	R
0.2	C	S	S	R	R	R	R	R	R
0.3	C	S	S	R	R	R	R	R	R
0.4	C	S	R/S	R	R	R	R	R	R
0.5	C	S	R/S	R	R	R	R	R	R
0.6	C	C/S	R/S	R	R	R	R	R	R
0.7	C	C/S	S	R/S	R	R	R	R	R
0.8	C	C	R	R	R	R	R	R	R
0.9	C	C	C	R	R	R	R	R	R

Note: This design assumes that the first visit does not have a systematically different detection probability than subsequent visits.

Specht et al. (2017) *Methods in Ecology and Evolution*
Reich (2020) *Biometrics*

“Mixed sampling design” “Double sampling design” / “Fractional replication”

- visit J_S sites once, J_R sites up to K times

	Mixed				
True state	**1**	**2**	**3**	**4**	**5**
1	1	0			
1	0				
1	0	0	1	1	0
1	0	0	0		
0	0				
1	1				
0	0				
0	0	0			
1	0				

“Mixed sampling design” “Double sampling design” / “Fractional replication”

- visit J_S sites once, J_R sites up to K times

Proportion of survey effort that should be conducted at single-visit sites.

p	**ψ**								
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
0.1	0	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0	0
0.3	0	0	0	0	0	0	0	0	0
0.4	0	3	0	0	0	0	0	0	0
0.5	6	1	0	0	0	0	0	0	0
0.6	0	0	0	12	4	0	0	0	0
0.7	9	5	0	0	0	0	0	0	0
0.8	33	30	26	21	14	5	0	0	0
0.9	56	54	51	48	44	39	31	17	0

Conclusions

It is only benefitial to plan for single visits when the species is very easy to detect.

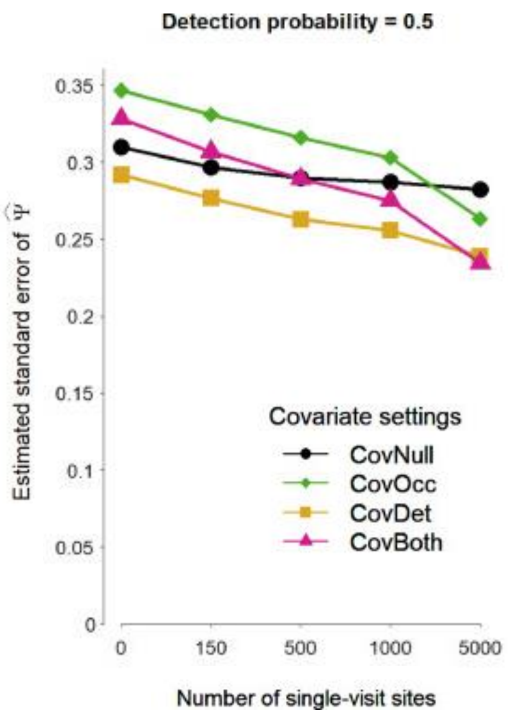
In all other cases, repeated visits at all sites yield better results than mixed designs.

MacKenzie & Royle (2005) *Journal of Applied Ecology*

“Mixed sampling design” “Double sampling design” / “Fractional replication”

- visit J_S sites once, J_R sites up to K times

Do single visits contribute any information at all?



Conclusion

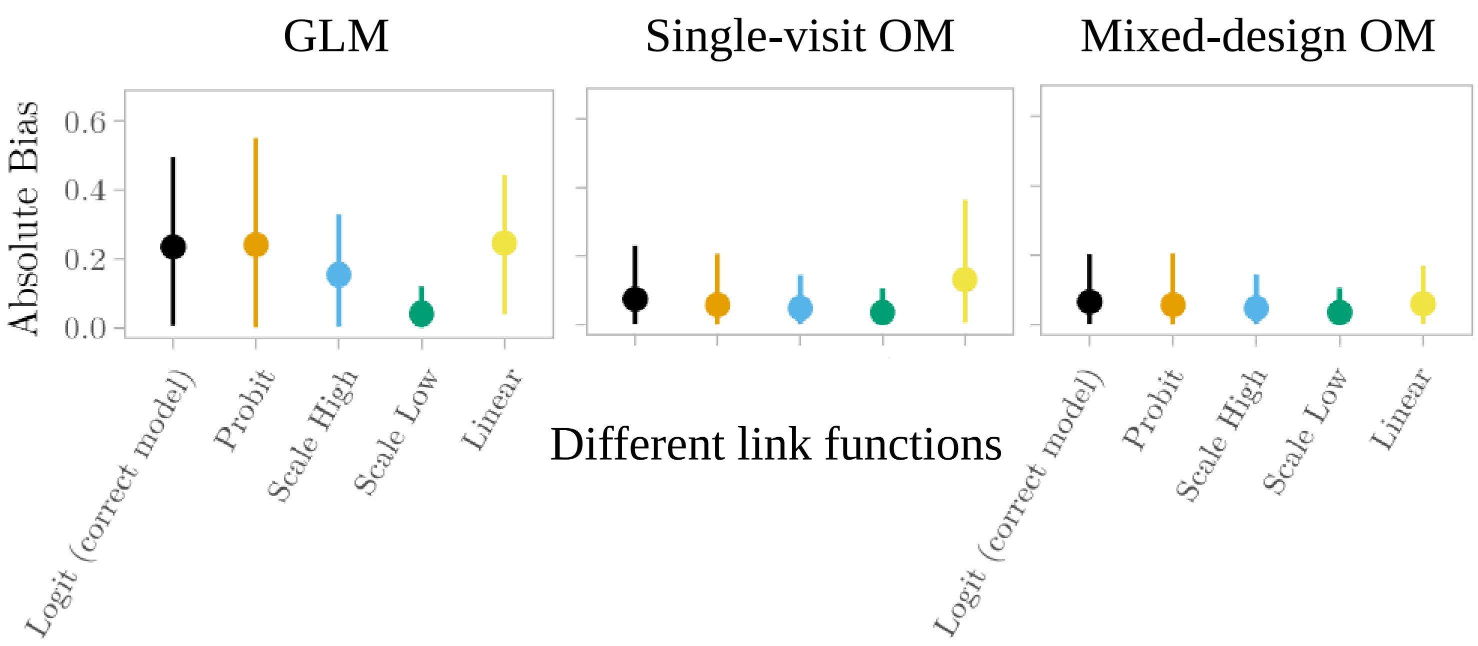
If combined with repeated-visit data, single-visit data contribute some information to the estimation of occupancy (and partly also of detection), especially when occupancy and detection are each explained by a **continuous covariate**.

von Hirschheydt et al. (2023) *Basic and Applied Ecology*

“Mixed sampling design” “Double sampling design” / “Fractional replication”

- visit J_S sites once, J_R sites up to K times

Do so few repeated visits make any difference in parameter estimation?



Conclusion

An **occupancy model fitted to mixed data** with only a few repeated visits still **performs better than a single-visit occupancy model or a GLM** that ignores imperfect detection.

Doser & Stoudt (2024) *Methods in Ecology and Evolution*

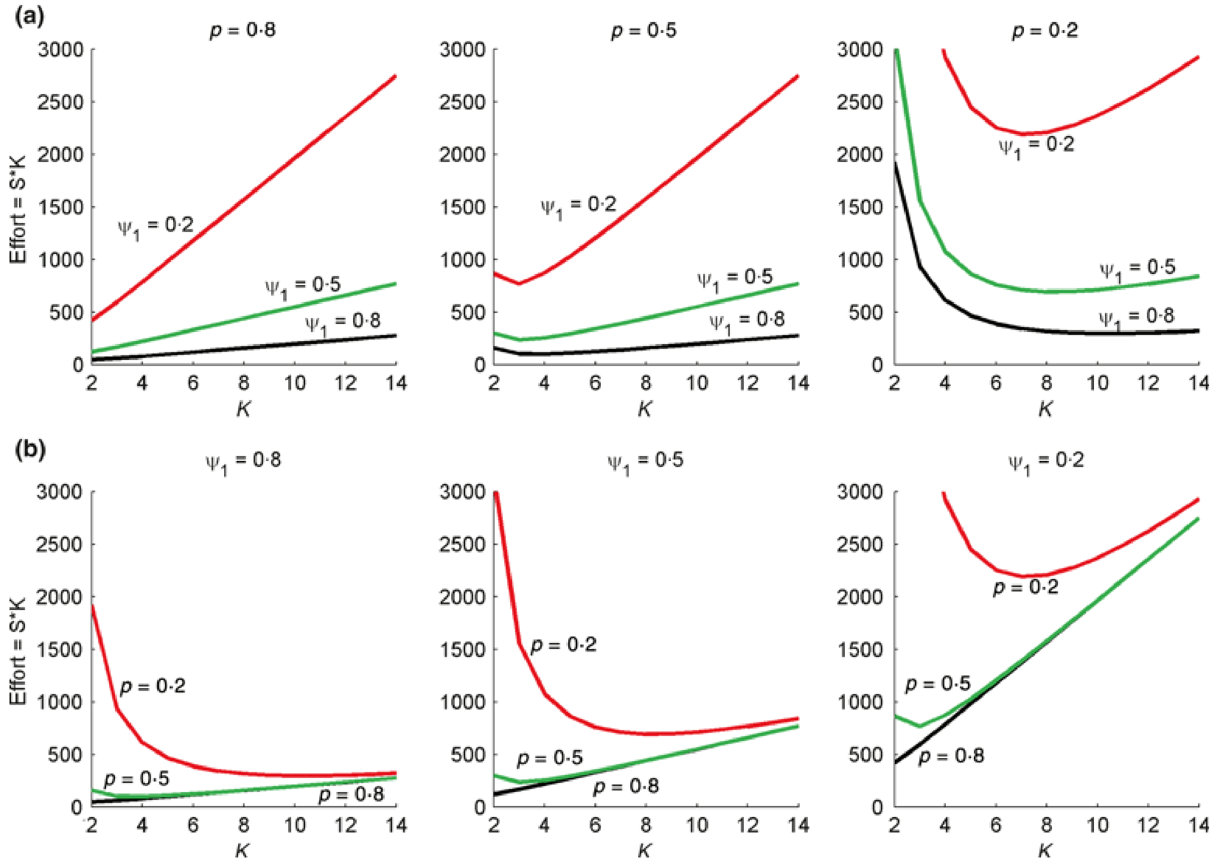
Occupancy dynamics

Goal: estimate change in occupancy over time with some degree of certainty

Occupancy dynamics

Goal: estimate change in occupancy over time with some degree of certainty

→ *find minimum survey effort to achieve a power of 0.8 when true decline is 0.5, for varying K and different levels of starting occupancy and detectability*



Conclusions

- with low *p* and low *psi* and few repeated visits, it requires huge effort to detect a change with certainty
- when *p* is low, increasing *K* towards the optimal value yield a great improvement in power
- when *p* is high, increasing K above 2 does not increase power

Guillera-Arroita & Lahoz-Monfort (2012) *Methods in Ecology and Evolution*

Additional heterogeneity or error

detection heterogeneity

- variation in abundance
- unmodelled environmental covariate
- observer differences

Royle (2006) *Biometrics*

false-positive sampling error

- standardization of sampling methods
- two types of observation certainties/methods

Royle & Link (2006) *Ecology*
Miller et al. (2011) *Ecology*
Ruiz-Gutiérrez et al. (2016) *Methods in Ecology and Evolution*

availability for detection

- habitat use
- undetectable life stages

Kéry & Schmidt (2008) *Community Ecology*
Efford & Dawson (2012) *Ecosphere*
DiRenzo et al. (2022) *Methods in Ecology and Evolution*

spatial pattern

- unmodelled covariates
- spatial autocorrelation

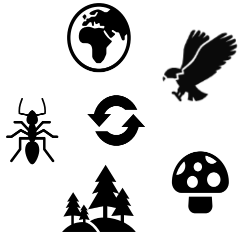
Guélat & Kéry (2018) *Methods in Ecology and Evolution*
Doser et al. (2022) *Methods in Ecology and Evolution*

What is your goal?

- Estimate occupancy with the greatest possible precision?
- Evaluate detection probability of a new sampling method?
- Detect a supposed decline with some degree of certainty?
- Predict colonization and future distribution?
- Investigate co-occurrence patterns?
- Analyse local population dynamics?
- Minimize type I or type II error?

Yoccoz et al. (2001) *Trends in Ecology & Evolution*

What is your system?



- single/multiple species
- sessile/mobile species
- scale (interpretation of occupancy and detection)
- seasonality
- period of closure
- destructive sampling
- probability of false-positive detections
- degree of spatial correlation
- cost of establishing new sites
- logistic constraints

Static systems

- expected occupancy probability
- expected detection probability
- expected detection heterogeneity
- expected false-positive error
- dependence between sites (transect sampling)

Dynamic systems

- expected rate of change (long-term trend)
- expected fluctuation/temporal variation
- expected local colonization/extinction rates

How to find the suitable design?

Math

Numerical optimization or asymptotic approximation of the function that describes the variable of interest (precision, statistical power, etc.)

Simulation

1. simulate true occupancy and detection/nondetection data under possible scenarios
2. analyze data with the intended model
3. compare variable of interest (precision/bias of the estimator, probability of type I error, probability of type II error (1-statistical power)

- easier for non-mathematicians
- forces to understand the data-generating and data-analyzing process
- especially useful for small sample sizes

Bailey et al. (2007) *Ecological Applications*
Guillera-Arroita & Lahoz-Monfort (2012) *Methods in Ecology and Evolution*

Simulation example

Simulate data to see how precision of the occupancy estimate depends on

- occupancy and detection probability of the species of interest
- the distribution of survey effort in a standard sampling design

What would the optimal number of repeated visits be for different species?

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Additional literature 1

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