11.0 Appendix A

Table A1. Summary of the assumptions and pros/cons of the different modelling approaches (adapted from Wearn & Glover-Kapfer [2017] and Clarke et al. [2022]).

Objective	Approach	Assumptions	Pros	Cons	References
Species inventory	Species inventory	• No formal assumptions[1]	• Maximum flexibility for study design (e.g., camera days per camera location or use of lure[2])[1]	• Not reliable estimates for inference ("considered as unfinished, working drafts")[1]	[1] Wearn & Glover-Kapfer, 2017 [2] Rovero et al., 2013 [3] MacKenzie et al., 2002 [4] MacKenzie et al., 2006 [5] Lambert, 1992 [6] Mullahy, 1986 [7] McCullagh & Nelder, 1989 [8] Zorn, 1998 [9] Royle & Nichols, 2003 [10] MacKenzie et al., 2006 [11] Karanth & Nichols, 1998 [12] Karanth, 1995 [13] Clarke et al., 2023 [14] Noss et al., 2003 [15] Kelly et al., 2008 [16] Moeller et al., 2018
Species richness	Species richness	• Cameras are randomly placed[1] • Cameras are independent[1] • detection probability of different species is equal[1] ("True" species richness estimation involves attempting to correct for "imperfect detection"[1])	• Fundamental to ecological theory and often a key metric used in management[1] • Simple to analyze, interpret and communicate[1] • Models exist to estimate asymptotic species richness, including unseen species (simple versions of these models - EstimateS and the "vegan" R-packages)[1]	• Dependent on the scale (as captured in the species-area relationship)[1] • All species have equal weight in calculations, and community evenness is disregarded[1] • Insensitive to changes in abundance, community structure and community composition[1]	
Species diversity	Species diversity	• Cameras are randomly placed[1] • Cameras are independent[1] • The detection probability of different species remains the same[1]	• Captures evenness and richness (although some indices only reflect evenness)[1] • Most indices are easy to calculate and widely implemented in software packages (e.g., EstimateS and "vegan" in R)[1]	• Many diversity indices exist, and it can be difficult to choose the most appropriate[1] • Interpretation/communication not always straightforward[1] • Insensitive to changes in community composition[1] (though this may be conditional on study design)	
Species diversity	β-diversity	• Can be used to track changes in community composition[1] • Plays a critical role in effective conservation prioritization (e.g., designing reserve networks)[1] • Important for detecting changes in the fundamental processes[1]	• Many measures; no single best measure for all purposes[1] • Comparing measures across space, time and studies can be very difficult[1] • Scale-dependent (i.e., the size of the communities that are being included)[1]		
Occupancy[3]	Occupancy models[3]	• Closed to changes in occupancy[3] (abundance is constant)[4] • Sites and detections are independent[4] • The probability of occupancy and detection are constant across all sites	• Does not require individual identification[4] • Just requires detection/non-detection data for each site[1]	• Occupancy[3] only measures distribution; it may be a misleading indicator of changes in abundance[1] • Interpretation/communication of results may not be straightforward (if the scale	

Objective	Approach	Assumptions	Pros	Cons	References
		within a stratum or can be modelled using covariates[4] • Species are not misidentified[4]	• Relatively easy-to-use software exists for fitting models (PRESENCE, MARK, and the "unmarked" R package)[1] • "Open" models exist that allow for the estimation of site colonization and extinction rates[1,4] • Multi-species occupancy models[3] allow the inclusion of interactions among species while controlling for imperfect detection[1]	of movement is much larger than the camera spacing the results should be interpreted as "probability of use" rather than occupancy)[1]	[17] Chandler & Royle, 2013 [18] Borchers & Efford, 2008 [19] Efford, 2004 [20] Royle & Young, 2008 [21] Royle et al., 2009
Relative abundance indices	Poisson Zero-inflated Poisson (ZIP)[5] Negative binomial (NB)[6] Zero-inflated negative binomial (ZINB)[7] Hurdle models[8] Other	• Since used for many approaches, many assumptions exist[1]	• Simple to calculate and technically possible (even with small sample sizes when robust methods might fail)[1] • Relative abundance indices often do correlate with abundance[1] • Calibration with independent density estimates is possible[1]	• Difficult to draw inferences (a large number of assumptions); comparisons across space, time, species, and studies are difficult[1] • Requires stringent study design (e.g., random sampling, standardized methods)[1]	[22] O'Brien et al., 2011 [23] Doran-Myers, 2018 [24] Morin et al., 2022 [25] Green et al., 2020 [26] Parmenter et al., 2003 [27] Noss et al., 2012
Absolute abundance; Unmarked population	Royle-Nichols model[9,10]	• Individual detection probability is constant[1]	• Can relax assumption of constant abundance[1] • Abundance is a fundamental parameter in wildlife research and monitoring[1] • Can be applied to unmarked species[1] • Only requires detection/non-detection data for each site (not counts)[1] • May be used in models with relative abundance to control for imperfect detection[1]	• Assumes a relatively specific relationship between local abundance and species-level detection probability[1] • Depends on sampling area[1] • Requires all or some of a population to be marked[1] • No dedicated, simple software for this model (but can be implemented in MARK and the "unmarked" package in R)[1]	[28] Sollmann et al., 2013a [29] Sollmann et al., 2013b [30] Rich et al., 2014 [31] Whittington et al., 2018 [32] Efford et al., 2009b
Population size / Absolute abundance / vital rates /	Capture-recapture (CR) / capture-mark-recapture (CMR)[11,12]	• Demographically closed (i.e., no births or deaths)[1] • Geographically closed (i.e., no immigration or emigration)[1]	• May be used as a relative abundance index that controls for imperfect detection[1] • Easy-to-use software exists to implement (e.g., CAPTURE); MARK	• Requires that individuals are distinguishable.[1] (However, CR[11,12] has also been used to estimate abundance of species that lack natural markers but that have phenotypic	[33] Royle et al., 2014

Objective	Approach	Assumptions	Pros	Cons	References
Density; Marked population		• Each individual has at least some probability of being captured[2] • Overall sampled area should encompass full extent of individuals movements[2,11] • Activity centres are randomly dispersed and stationary[13]	Implements more complicated models with covariates (and must be used for mark-resight modelling)[1] • Can use the robust design with "open" models to obtain recruitment and survival rate estimates[1]	and/or environment-induced characteristics[2,,14,15] When the sample size is large enough to reliably estimate density with CR,[11,12] individuals are unlikely to have a unique marker[2,14,15]) • Dependent on the surveyed area, which is difficult to track and calculate[1] • Requires a minimum number of captures and recaptures[1] • Relatively stringent requirements for study design (e.g., no "holes" in the trapping grid)[1] • Geographic closure at the plot level, which is often unrealistic[16] • Assumes a specific relationship between abundance and detection[1] • Density cannot be explicitly estimated because the true area animals occupy is never measured (only approximated)[17]	[34] Augustine et al., 2019 [35] Burgar et al., 2018 [36] Sun et al., 2022 [37] Sollmann, 2018 [38] Augustine et al., 2018 [39] Davis et al., 2021 [40] Rowcliffe et al., 2008 [41] Rowcliffe et al., 2013 [42] Rowcliffe et al., 2014 [43] Rowcliffe et al., 2016 [44] Rowcliffe et al., 2011 [45] Cusack et al., 2015 [46] Nakashima et al., 2017 [47] Meek et al., 2016 [48] Anile & Devillard, 2016 [49] Huggard, 2018 [50] Becker et al., 2022 [51] Warbington & Boyce, 2020
Density / population size; Marked population	Spatially explicit capture recapture (SECR)[18-21] (also referred to as Spatial capture-recapture [SCR])	• Individuals do not lose marks or are misidentified[1] • All animals have an equal probability of capture (or, for spatially explicit models, an equal probability of capture for a given distance from the centre of their home range)[1] • Captures of different individuals are independent[1] • No behavioural response to being trapped or marked[1] • Sampling occasions are independent[1] • Population is demographically closed (i.e., no births or deaths)[1] • For conventional models, geographically closed, i.e., no immigration or emigration)[1]	• Produces direct estimates of density or population size for explicit spatial regions[17] • Allows researchers to mark a subset of the population/to take advantage of natural markings[1] • Estimates are fully comparable across space, time, species and studies[1] • Density estimates obtained in a single model, fully incorporate spatial information of locations and individuals[1] • Both likelihood-based and Bayesian versions of the model have been implemented in relatively easy-to-use software (DENSITY and SPACECAP, respectively, as well as associated R packages)[1]	• Requires that individuals are identifiable[1] • Requires that a minimum number of individuals are trapped (each recaptured multiple times ideally)[1] • Requires that each individual is captured at a number of camera locations[1] • Multiple cameras per station may be required to identify individuals; difficult to implement at large spatial scales as it requires a high density of cameras[13,24] • May not be precise enough for long-term monitoring[25] • Cameras must be close enough that individuals come into contact with multiple cameras[1,17]	

Classification: Protected A

Objective	Approach	Assumptions	Pros	Cons	References
		• Spatially explicit models have further assumption about animal movement.[1,18,21,22] These include: • Home ranges do not change during the survey[1] • Captures does not affect movement patterns[1] • Random placement with respect to the distribution and orientation of home ranges[1] • Distribution of home range centres follows a defined distribution (Poisson, or other, e.g.,)[1]	• Flexibility in study design (e.g., "holes" in the trapping grid)[1] • "Open" SECR[18-21] models exist that allow for estimation of recruitment and survival rates[1] • "Avoid ad-hoc definitions of study area and edge effects"[23] • SECR[18-21] accounts for variation in individual detection probability; can produce spatial variation in density; SECR[18-21] more sensitive "to detect moderate-to-major populations changes" (+/-20-80%)[13,24]	• ½ MMDM (Mean Maximum Distance Moved) will usually lead to an under - estimation of home range size and thus overestimation of density[1,26,27]	[52] Howe et al., 2017 [53] Palencia et al., 2021 [54] Gilbert et al., 2020 [55] Twining et al., 2022 [56] Bessone et al., 2020 [57] Moeller et al., 2018
Density; Marked population	Spatial mark-resight (SMR) (type of SCR model)[17,28,29]	• Demographic and geographic closure of the population during the survey[1] • Detections are independent[29] • Detection probability decays with increasing distance of the camera from the activity centre[29,30] • Animals have stable activity centres[30] • Individual marks are not lost (for maximum precision), but SMR[17,28,29] does allow for inclusion of marked but unidentified resighting detections[28,31] • The number of marked animals present is known before resightings[28,30] • Animals are ungrouped[29] • Counts of unmarked animals are modeled with a Poisson distribution[30] • Cameras randomly placed with respect to activity centres[28] • Marked animals are a random sample of the population with home ranges located inside the state space[29,30] • All animals have stable activity centres within home ranges where detection probability is greatest[28,32]	• Estimates are fully comparable to SECR[18-21] of marked species[1] • Can be applied to a broader range of species than SECR[18-21][1] • Allows researcher to take advantage of natural markings[1] • Allows researcher to mark a subset of the population (note - precision is dependent on number of marked individuals in a population)[1]	• Animals may have to be physically captured and marked if natural marks do not exist on enough individuals[1] • All individuals must be identifiable[1] • Allows for density estimation for a unmarked population, but the precision of the density estimates are likely to be very low value[1] • Remains poorly tested with camera data, although it offers promise[1] • Density estimates are likely less precise than with SECR[18-21] or REM, unless a large proportion of the population have marks[1] • Requires sampling points to be close enough that individuals encounter multiple cameras[1]	[58] Loonam et al., 2021 [59] Bridges & Noss, 2011 [60] Rovero & Zimmermann, 2016 [61] Borchers & Marques, 2017

Objective	Approach	Assumptions	Pros	Cons	References
Density; Unmarked population	Spatial count (SC) (type of SCR model)[17,33]	• Camera must be close enough together that animals are detected at multiple cameras[13,17] • Population closure[13,17] • Independence of detections[13,17] • Activity centres randomly dispersed[13,17] • Activity centres are stationary[13,17]	• Does not require individual identification[13]	• Produces imprecise estimates even under ideal circumstances unless it is supplemented with auxiliary data (e.g., telemetry)[17,23,28,29] • Precision decreases with an increasing number of individuals detected at a camera"[24] (as overlap of home ranges of individuals' increases)[13,34] • Not appropriate for low density or elusive species when recaptures too few to confidently infer the number and location of activity centres"[13,35] • Not appropriate for high-density populations with evenly spaced activity centres (camera[-specific] counts will be too similar and impair activity centre inference)"[13] • Ill-suited to populations that exhibit group-travelling behaviour"[13,36] • Study design (camera arrangement) can dramatically affect the accuracy and precision of density estimates"[13,37] • Cameras must be close enough that animals are detected at multiple camera locations (may be challenging to implement at large scales as many cameras are needed)"[13,17]	
Density / population size; Partially Marked population	Spatial Partial Identity Model (Categorical SPIM; catSPIM)[13,34,36] (Extension of SC model using animal traits (e.g. Sex Class, antler points) and model parameters)	• Same as SC[13,34,36] • Each categorical identifier (e.g., Sex Class, collar, etc) has fixed number of possibilities (e.g., male/female, collared/not collared)[36] • All possible values of categorical identifiers occur in the population with probabilities that can be estimated[13,34,36] • Every individual is assigned "full categorical identity" (i.e., "set of traits given all categorical identifiers and possibilities")[13,34]	• May produce more precise and less biased density estimates than SC with less information[13,36]	• Sensitive to non-independent movement (e.g., group-travel; can cause over-dispersion and bias estimates[13,36]); may limit application to solitary species only[13,36] • May produce be less reliable/accurate estimates for high-density populations[13,36] • To few categorical identifiers/ possibilities can result in mis-assignments and overestimating density[13,34,26]	

Objective	Approach	Assumptions	Pros	Cons	References
		• There is no change in an individual's identity trait during the survey period (e.g., antlers present/absent)[34]			
Density / population size; Partially Marked population	Spatial Partial Identity Model (2-flank SPIM)[13,38] (extension of SCR model augmented with data from partially-identifying images)	• Same as SCR[13,38] • Capture processes for left-side, right-side and both-side images are independent[13,38]	• Same as SCR[13,38] • Improved precision of density estimates relative to SCR[13,38,39] • Many study designs can be used (paired sample stations, single camera locations, and hybrids of both paired- and single camera locations[13,38,39] • Can be used with single-camera and hybrid sampling designs, and therefore requires fewer cameras (or sample more area) than SCR[13,38] • May be more robust to non-independence than SC[34,38]	• Computationally intensive[13,38] • Increased precision is less pronounced in high-density populations[13,38]	

Density; Unmarked	Random encounter models (REM)[40,41]	• Demographic and geographic closure[23,40]
		• Random with respect to animal movement[1,40]
		• Animal movement is not affected by the cameras[1,40]
		• Independent "contacts" between camera locations can be accurately counted[1,40]
		• Unbiased estimates of animal activity levels and animal speed can be obtained[1,42,43]
		• Camera's detection zone can be approximated well using a 2D cone shape, defined by the radius and angle parameters[44]
		• If activity and speed are to be estimated from camera data, two additional assumption:
		  ○ All animals are active during the peak daily activity[42]
		  ○ Animals moving quickly past a camera are not missed[43]
			• Flexible study design (e.g., "holes" in grids allowed, camera spacing less important)[1]
			• Can be applied to unmarked species[1]
			• Allows community-wide density estimation[1]
			• Outputs also include informative parameter estimates (i.e., animal speed and activity levels, and detection zone parameters)[1]
			• Comparable estimates to SECR[18-21][1]
			• Does not require marked animals or identification of individuals[23,40]
			• Can use camera spacing without regard to population home range size[23,40]
			• Direct estimation of density; avoids ad-hoc definitions of study area[40]
				• Requires relatively stringent study design, particularly (e.g., random sampling and use of bait or lure)[1]
				• Requires independent estimates of animal speed or measurement of animal speed within videos[1]
				• No dedicated, simple software[1]
				• Random relative to animal movement, grid preferred, avoid multiple captures of same individual, area coverage important for abundance estimation[2]
				• Possible sources of error include inaccurate measurement of detection zone and movement rate[41,45]	

Objective	Approach	Assumptions	Pros	Cons	References
Density; Unmarked	Random encounter and staying time (REST)[46]	• The population is closed (animal density is constant during the survey)[40] • The detection probability is perfect[1] (p = 1) unless otherwise modelled[46] • Camera locations are representative of the available habitat[46] • Cameras are randomly placement with respect to the spatial distribution of animals[46] • Animal movement and behaviour are not affected by cameras[46] • Observations are independent[46] • The observed distribution of staying time in the focal area fits the distribution of movement[46] • The observed staying time must follow a given parametric distribution[46]	• Provides unbiased estimates of animal density, even when animal movement speed varies, and animals travel in pairs[46]	• Attraction or aversion to cameras is exhibited in some species[47] and could affect the time within the detection zone and subsequently affect estimates of density[23] • Requires accurate measurements of the area of the camera detection zone, which has been a challenge in previous studies[23,44-46,48] • Mathematically challenging[45]	
Density; Unmarked	Time in front of the camera (TIFC)[49-51]	• Cameras are placed randomly, or representative relative to animal movement[50] • No influence of cameras on animal movement[50] • Reliable detection of animals in part of the camera's FOV (at least)[50]	• Does not require individual identification[51] • Makes no assumption about home range[51] • Comparable to estimates from SECR[18-21]51	• Requires careful calculation of the effective area of detection[51] • A high level of measurement error[50]	
Density; Unmarked	Distance sampling (DS)[52,61]	• Random or systematic random placements consistent with the assumption that points are placed independently of animal locations[52] • Placed randomly with respect to animal movement [53] • Certain detection at distance 0[53] • Certain detection at focal area[53] • Closed population[53] • Animal movement and behaviour not affected by the cameras[53]	• A shortcut to controlling for variation in detection distances by only counting individuals within a short distance with an unobstructed view, and well sampled across cameras and species[1] • Density estimates are unbiased by animal movement "since camera-animal distance is measured at a certain instant in time (intervals of duration *t* apart)"[13,52] • Can be applied to low-density populations[13,53]	• May require discarding a portion of the dataset (when the best fitting model truncates the dataset)[1] • Biased by movement speed[53] • Best suited to larger animals; the smaller the focal species, the lower [wildlife] cameras must be set, which reduces the depth of the viewshed, and thus sampling size and the flexibility of the model"[13,52] • Does not permit inference about spatial variation in abundance (unless using hierarchical distance which can model	

Objective	Approach	Assumptions	Pros	Cons	References
		• Animals detected at initial locations (e.g., they do not change course in response to the camera prior to detection)[53] • Distances are measured exactly (however if the data from different distances will be grouped ("binned") for analysis later, an accuracy of +/- 1m may suffice)[53] • Observations are independent events[53] • Snapshot moments selected independently of animal locations[53]	• Does not require individual identification[52]	spatial variation as a function of covariates)[13,54] • "Calculating camera-animal distances can be labour-intensive and time-consuming (However, recently developed techniques (e.g., Johanns et al., 2022) show promise for simplifying and automating the process)"[13] • Requires good understanding of the focal populations' activity patterns; density estimates can be biased (e.g., under-estimated) when regular periods of inactivity are not accounted for (using detection times to infer periods of activity may help overcome this limitation)"[13,52,53] • Tends to underestimate density[13,52,55] • Low population density and reactivity to cameras may be major sources of bias"[13,56]	
Density; Unmarked	Time-to-event (TTE) model[57]	• Demographic and geographic closure[57,58] • Locations randomly placed, systematic, systematic random[57] • Independent detections in space and time[57] • Spatial counts of animals (or counts in equal subsets of the landscape) are Poisson-distributed[58] • Accurate estimate of movement speed[58]	• Can be efficient for estimating abundance of common species (with a lot of images)[57]	• Requires independent estimates of movement rate (difficult to attain without telemetry data)[57] • Assumes that detection probability is 1 (or apply extension to account for imperfect detection)[57]	
Density; Unmarked	Space-to-event (STE) models[57]	• Demographic and geographic closure[57] • Locations randomly placed[V] • Independent detections in space and time[57] • Spatial counts of animals in a small area (or counts in equal subsets of the landscape) are Poisson-distributed[58]	• Can be efficient for estimating abundance of common species (with a lot of images)[57] • Does not require estimate of movement rate[57]	• Assumes that detection probability is 1[57]	

Objective	Approach	Assumptions	Pros	Cons	References
Density; Unmarked	Instantaneous sampling (IS)[57]	• Demographic and geographic closure[57] • Locations randomly placed[57] • Independent detections in space and time[57]	• Can be efficient for estimating abundance of common species (with a lot of images)[57] • Flexible assumption of animals' distribution[57]	• Requires accurate counts of animals[57] • Assumes that detection probability is 1[57] • Reduced precision[57]	
Behaviour (Diel activity patterns, mating, boldness, etc.)		• Assumptions vary depending on the behavioural metric[1] • For studies of activity patterns and temporal interactions of species: activity level is the only factor determining detection rates; animals are active when camera detection rate reaches its maximum in daily cycle[33,60]	• Can detect difficult to observe behaviours (i.e., boldness, or mating)[59] • Long-term data on behavioural changes that would be difficult to obtain otherwise (i.e., time-limited human observers, or costly GPS collars)[59] • Can monitor behaviour in response to specific locations (i.e., compost sites, which might be more difficult using GPS collars for example)[60] • Can evaluate interactions between species[60]	• Behavioural metrics may not reflect the behavioural state (inferred)[60] • Biases associated with equipment (i.e., presence of the camera itself may change behaviour studied)[60] • Difficult to consider individual variation[60]	