

Evaluation of the analysis of distance sampling data: a simulation study

Utvärdering av avståndsanalys av inventeringsdata: en simuleringsstudie

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Abstract

Distance sampling is used to estimate number of individuals in an area of interest. The idea is that with known distances to the observed individuals, one can model the probability of detection in relation to distance and thereby account for individuals that were not detected. Distances can be recorded either exactly or in discrete categories. In this study I validated the method using simulated distance sampling data for two hypothetical bird species and compared the estimated density values to the known true densities. Generally the true densities and numbers of individuals were very similar to (and always within the 95% confidence interval of) the parameter estimates from the analysis of the simulated data. The analyses were also robust to modifications of the data such as truncation and

grouping of the distances into discrete categories. The confidence intervals increased, however, when using only two distance groups. Given that critical assumptions of the model can be met in the field situation, distance data can thus be used in a wide range of bird studies to calculate reliable density estimates.

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Introduction

Distance sampling is a biological survey method aimed to provide estimates of density and number of individuals in the sampled area. The method can be applied to point and line transects for a wide variety of systems and species (Sutherland 1996). In addition to recording the number of individuals and species identity, one also registers the distance between each identified individual and the line or point (either as exact measurements or grouped into discrete distance ranges). This procedure enables the investigator to account for individuals present but not detected in the survey, provided that they are potentially observable during the census. More specifically the distances recorded are visualised in a histogram and a detection function is modelled onto the data. This detection function is then used to estimate the proportion of individuals in the effectively surveyed area that were not detected and an estimate of the true density of individuals is calculated. The density estimate can then be multiplied by the total size of the area of interest

to obtain a measure of the true number of individuals (Bibby et al. 2000).

Application to bird studies

Distance sampling has been applied successfully to a large number of bird species in different environments (see for example Marsden 1999, Cimprich 2009, Handel et al. 2009), and has been shown to give more robust estimates of population trends than relative estimates of bird densities, for example line or point transect counts without distance recording (Norvell et al. 2003). This is because the assumption for relative density estimates, that the probability of detection function remains constant between different time points, is often likely to be violated because of changes in conditions such as observers, weather, or habitat. However, other studies have also emphasised practical and theoretical problems with distance sampling applied to bird surveys and in many cases more sophisticated protocols like multiple observer surveys are advised to be able to control for violations of the various

assumptions of distance sampling methodology (Kissling & Garton 2006, Southwell & Low 2009).

Important practical considerations

Before performing a distance sampling survey there are a number of practical limitations to consider. There are several assumptions regarding the data collection that need to be met in order to get reliable density estimates from the analysis; some of these are discussed below. In general these assumptions require a well planned study and carefully performed field work with well trained field workers (Buckland et al. 2001).

Correct measurement of distances

One important assumption is that the distances are measured correctly. Bias in the distance measurement will inevitably lead to bias in the estimate of individual densities. This is especially important for point counts since measurement errors will increase geometrically with distance (Bibby et al. 2000). Laser rangefinders can be helpful for measuring distances to the birds or to the vegetation patches from which they are singing. Also note that for line transects the measure analysed is the closest distance from the bird to the line and not to the observer. This can be calculated by trigonometry by also recording the angle between the line and the bird from the observation point (Figure 1a). If the exact measurement of distances is impractical there is also an option to record distances into two or more discrete categories (Figure 1b–c).

Representative sample

In order to extrapolate the density estimates from the sampled transects into the entire study area it is important that the transects are representative of the area as a whole (Ekblom 2007). This can be achieved using a variety of randomisation or systematic sampling methods. For more information about sampling theory and survey design, please consult a statistics textbook (for example Fowler et al. 1998). It is recommended that the sample contains at least 20 different lines or points across the study area to obtain a reliable estimate of variance (Buckland et al. 2001).

Birds do not move in relation to the observer

If birds are attracted to or move away from the observer before detection, the distances will be

systematically biased, causing an underestimate or overestimate of the species density. Also for point counts it is important that counting periods are short enough that random movements of birds around the study area will not cause the number of detections close to the observer to be biased high (Buckland 2006).

Birds on the transect are always detected

To get reliable estimates of the detection function it is important that individuals on or very close to the line (or point) have a 100% detection probability. If this assumption is likely to be violated it is possible to account for missed birds by having two transect lines parallel to each other being censused simultaneously (Buckland et al. 2001), or by having two observers counting simultaneously at a point (Kissling & Garton 2006). There is also an option to left-truncate the data during analysis if this assumption seems to have been systematically violated.

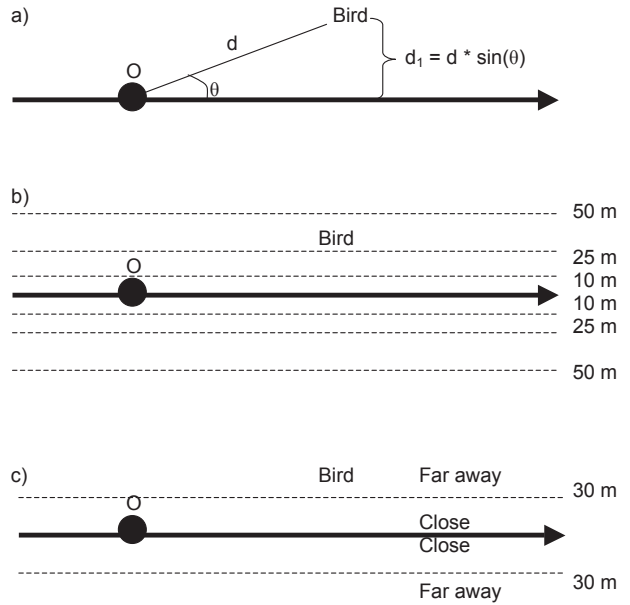
Correct species identification

It is also important that the species are correctly identified for all individuals registered. If the distance is too large, or observation too brief, for correct species identification such an observation should not be registered. Recordings of bird songs are available for many geographic areas and can be used to learn to identify species that are more often heard than seen.

Large number of observations

In order to reliably fit a detection function to the data, it is generally advised that sample sizes are rather large. As a rule of thumb 60 to 80 observations are a minimum to produce reliable density estimates (Buckland et al. 2001). In many investigations this number of observations may be hard to obtain for uncommon species. However, species with similar detection probabilities may be pooled in the analysis to increase the sample size and provide a more robust model fitting for the probability of detection function. Sample lines or points may also be surveyed multiple times during a season to obtain the number of detections required for analysis. For some species or restricted study areas, however, it may be necessary to choose a different census method (for example a territory mapping scheme).

Figure 1. Different possible strategies for sampling distance data in a line transect survey. The thick arrow indicates the transect line and the direction of travel. a) The exact distance (d_1) between the bird and the transect line (thick arrow) is calculated using the measurement of distance (d) between bird and observer (O) and the angle from the observer between the line and the bird (θ). b) Estimating the distance between the bird and the line in four discrete distance groups (in this case 0–10 m, 10–25 m, 25–50 m and further away than 50 m). c) Estimating the bird to be close to or far away from the line (in this case with a cut-off value of 30 m). *Olika tänkbara strategier för att för att samla in avståndsdata vid en linjeinventering. Den tjocka pilen representerar linjen. a) Det exakta avståndet (d_1) mellan fågeln (Bird) och linjen kan räknas ut genom att mäta avståndet (d) mellan fågeln och observatören (O) samt vinkeln från observatören mellan linjen och fågeln (θ). b) Uppskattning av avståndet mellan fågeln och linjen i fyra diskreta avståndsklasser (i detta fall 0–10 m, 10–25 m, 25–50 m och längre bort än 50 m). c) Uppskattning om fågeln är nära eller långt bort från linjen (i detta fall med ett gränsvärde på 30 m).*



Aim of this study

The aim of the present investigation was to evaluate the analysis of distance sampling data, using a simulated line transect study of two hypothetical bird species with different densities and probabilities of detection. I also investigated how truncating and grouping of the distance data affected the analyses and estimates.

Materials and methods

Study area and species

The simulated study area was 5 km² large with an approximately rectangular shape and homogenous environment (similar probability to record an individual of a certain species and at a certain distance throughout the whole area). For each of the two bird species (A and B) territories of irregular shape and size were plotted covering the whole area and one singing male was placed randomly in each territory. The birds were not allowed to move during the simulated survey. The total number of singing males in the area was 185 for species A and 66 for species B.

Line transect census

Twenty transect lines were systematically spread over the study area and each line was surveyed

once for each of the two bird species. The lines were 1 km long and spaced approximately 250 m apart. The exact distance from the transect line to every singing bird in the area was measured with an accuracy of one meter. Two (one for each species) sigmoid probability functions (arbitrarily drawn on a grid paper) was used to determine the likelihood of an individual of being detected at a certain distance. For both species the probability to detect an individual decreased nonlinearly with the distance from the line. For species A there was a 50% probability of detecting an individual at a distance of 40 m from the line and for species B this distance was 130 m from the line. Species A thus corresponds to a rather cryptic species whereas species B was easy to observe also at longer distances. For both species the probability of detecting an individual on, or very close to (A: 0–15 m, B: 0–30 m) the transect was set to 1 (see criteria for reliable analysis of distance data in the Introduction). Zero probability of detection was reached at 90 m for species A and at 180 m for species B. For each distance measured between the transect and the bird, the probability of detection was registered from the probability function of the species in question (see above). A random number between 0 and 1 was then drawn, and if this was lower than the probability of detection the bird was defined as observed.

Analysis of distance data

Distance data generated by the simulation described above were analysed using the software Distance 5.0 (Thomas et al. 2005). For each analysis and species I fitted each of three different key detection functions (uniform, half-normal and hazard rate), with an additional optional series expansion (simple polynomial, cosine or hermite polynomial). The model with the smallest Akaike Information Criterion (AIC) value was chosen. In addition I also inspected the fit of the functions to the data manually using the histograms produced in Distance. For truncated analyses I discarded all observations further than 50 m from the line for species A and further than 125 m for species B. For analyses with data in four intervals I chose bins of

0–10 m, 11–25 m, 26–50 m and further away than 50 m for species A and 0–25 m, 26–50 m, 51–100 m and further than 100 m away for species B. When analysing data using only two intervals (close and far away) I set the cut-off point to 30 m for species A and 50 m for species B.

Results

Results from the distance sampling

A total of 70 singing males of species A (mean 3.5 per transect line) and 69 of species B (mean 3.45 per transect line) were observed during the simulation. Mean observed distance between the line and the bird was 26.6 m (range 1 to 77) for species A and 66.0 m for species B (range 0 to 157). For species A the observations fell into a rather smooth

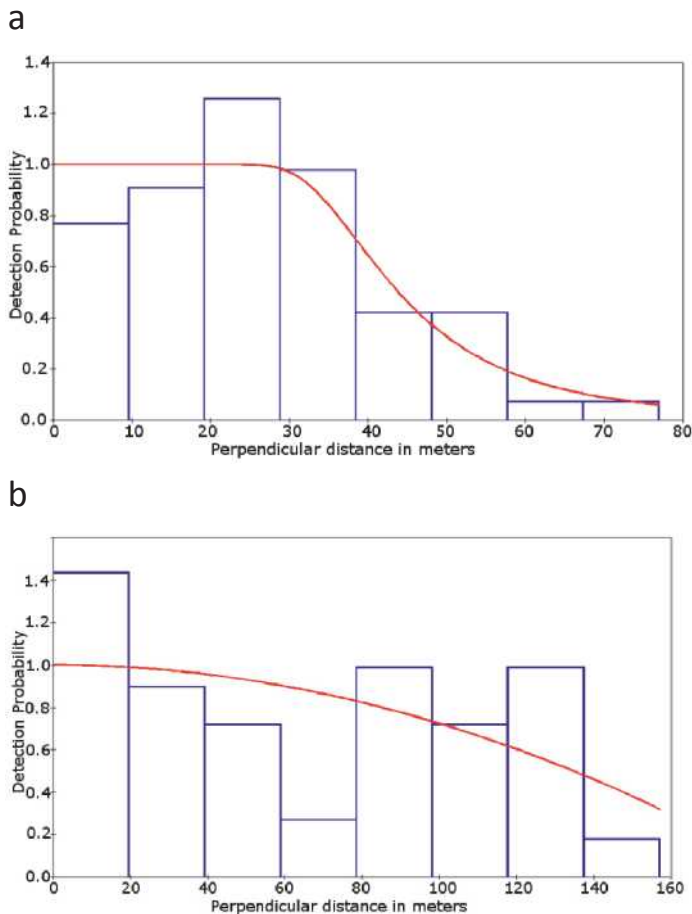


Figure 2. Histograms of the detection probability plotted against distance between the transect line and the observed birds. Fitted to the data is the modelled probability of detection function. a) Data for species A with a hazard rate key function without any series expansion terms fitted as the probability of detection curve. b) Data for species B with a uniform key function with one simple polynomial adjustment term fitted.

Histogram över sannolikheten att fågeln har upptäckts som en funktion av avståndet mellan linjen och de observerade fåglarna. a) Data för art A med "Hazard rate key" kurva utan några serie-expansionstermer passad som upptäckbarhetsfunktion. b) Data för art B med en "Uniform key" kurva med en enkel polynomisk justeringsterm passad.

Table 1. Summary of the true and estimated (with 95% confidence intervals) densities (D, number of singing males per km²) and total number of singing males (N, number of individuals) of the two simulated species (A and B) using different analysis specifications.

Sammanfattning av de verkliga och uppskattade (med 95% konfidensintervall) individtätheterna (D, antal sjungande hanar per km²) och antalet sjungande hanar (N, antal individer) av de två simulerade arterna (A och B) med olika typer av avståndsanalyser.

Species	Analysis	D	N
A	True values	37.0	185
	<i>Verkliga värden</i>		
	Exact distances	37.2 (27.2–50.7)	186 (136–254)
	<i>Exakta avstånd</i>		
	Right-truncated data	37.3 (27.0–51.5)	186 (135–257)
	<i>Högerkapade data</i>		
	Data in 4 distance bins	37.9 (28.2–50.8)	189 (141–254)
	<i>Data i 4 avståndskategorier</i>		
Data in 2 distance bins	39.3 (28.2–54.7)	197 (141–274)	
<i>Data i 2 avståndskategorier</i>			
B	True values	13.2	66
	<i>Verkliga värden</i>		
	Exact distances	14.2 (11.3–17.8)	71 (57–89)
	<i>Exakta avstånd</i>		
	Right-truncated data	12.4 (10.6–14.6)	62 (53–73)
	<i>Högerkapade data</i>		
	Data in 4 distance bins	14.7 (11.1–19.6)	74 (55–98)
	<i>Data i 4 avståndskategorier</i>		
Data in 2 distance bins	16.0 (11.7–21.9)	80 (58–110)	
<i>Data i 2 avståndskategorier</i>			

sigmoid distribution (Figure 2a) whereas for species B the observations were more randomly scattered (Figure 2b).

Estimates of density and absolute numbers

When using the original data for species A (all measured distances between transects and the birds) the hazard-rate key function (with no series expansion used) gave the smallest AIC of the different models and was thus the best fit to the data (Figure 2a). According to this model the density of birds was 37.2 singing males per km² and the number of singing males in the whole study area was 186 (Table 1). This is strikingly similar to the true values of 185 singing males and 37 individuals per km². For species B the uniform key function with a simple polynomial adjustment term was chosen based on AIC (Figure 2b). The analysis produced an estimate of 14.2 singing males per km² and a total of 71 singing males in the area as a whole (Table 1). These are slight overestimates but the true values (13.2 and 66) are still well within the 95% confidence limits of the estimates.

Effect of truncation of the data

For some datasets it is advised to use right truncation to decrease the effect of a few outliers on the model fitting. For species A the right truncation removed seven observations with observation distances exceeding 50 m. Again the hazard rate key gave the best fit to the data. According to this model the density of birds was 37.3 per km² and total number of singing males was still estimated to 186 (Table 1). For species A the right truncation thus had very little effect on the estimated parameters, but the confidence intervals around the estimates were increased slightly due to the smaller sample size (Table 1). With species B the right truncation led to seven observations with distances exceeding 125 m being removed. The model now best fitting the data was the uniform key without any adjustment terms (basically a straight line). The density was estimated to 12.4 singing males per km² and total number was 62, thus an underestimation (Table 1). These estimates for species B were highly dependent on the cut-off value used for the truncation, however, and when truncating a larger

number of the observations the density was generally instead overestimated (data not shown).

Effect of data in intervals

Under many circumstances it is impractical or even impossible to measure the distances from the line to the birds exactly. In such cases distance sampling can still be applied using discrete distance categories. Also in cases where exact measurements have been taken but measurement or rounding errors occur it may be advisable to group the data into bins before performing the model fitting. I tested this approach for analysing the simulated dataset by grouping the data into four or two discrete distance categories. For species A grouping into four distance categories gave an estimated density of 37.9 singing males per km² and a total number of 189 (Table 1). The model with the best fit to the data in this case was the uniform key with simple polynomial adjustments. For species B the best model for data in four categories was the uniform key using one cosine adjustment term. Now the estimated density was 14.7 per km² and the estimated number was 74 (Table 1).

The simplest approach for distance data collection is to group the distances into only two bins, close and far away, with a predetermined cut-off value. For species A this cut-off was set to 30 m. In this analysis several of the models had similar AIC values and the uniform key with simple polynomial adjustments was chosen after manually inspecting the fit to the histogram (the hazard rate functions cannot be fitted to datasets in only two distance categories due to lack of degrees of freedom). In this analysis the density (39.3 per km²) and number of singing males (197) were slightly overestimated. The true values were still, however, well within the 95% confidence limits (Table 1). Species B was analysed using a cut-off value of 50 m. Several different models had the same AIC values and again the uniform key with one simple polynomial adjustment term was chosen based on manual inspection of the fit to the data. Here the estimates were again slightly overestimated with a density of 16.0 per km² and number of singing males of 80 (Table 1). Also, the confidence intervals were larger than for the full data analysis. The estimates changed substantially when altering the cut-off value of the distance bins (data not shown).

Comparison of distance analysis with uncorrected counts

For species A the maximum distance of detection was 77 m and for species B it was 157 m. This means that the effective sampled areas were 3.08 (77×2×20) km² and 6.28 (157×2×20) km² for the two species, respectively. Dividing the number of males detected by the area sampled for each species, one would estimate uncorrected densities of 22.7 singing males per km² for species A (true value 37) and 11.0 per km² for species B (true value 13.2). This shows how density estimates that are not corrected for the probability of detection may be severely biased, especially in cryptic species.

Discussion

This study validates the use of analysis of distance sampling data to calculate estimates of density and absolute numbers of birds. The true density values generally fell very close to the estimated densities and well within the estimated 95% probability ranges. The results were generally rather robust against variations in the analyses used. For species B, however, the density estimates fluctuated somewhat depending on the specificities of truncation or grouping of the data (the true parameter values were always within the confidence limits though). In most real situations the efficiency of this kind of analysis will probably be limited by the need to meet the critical assumptions for distance sampling outlined in the Introduction. In particular great care should be taken to make observations of all individuals on or close to the transect (Bibby et al. 2000). To evaluate if this assumption is met in a real field study it may be wise to apply a double-observer approach, at least for part of the collected data (e.g., Kissling & Garton 2006).

If it is not possible to measure exact distances to a reasonable degree of accuracy it is recommended to collect distance data in discrete distance ranges instead. This simulation study indicates that such an approach will produce estimates of densities similar to those from exact distance data even in the case when only two distance ranges are applied (close and far away). The confidence intervals around the density estimates were however generally larger for grouped distance data than for exact measurements. It is also of crucial importance to choose the cut-off distance with care, to avoid biasing the results. The cut-off should be selected at a distance at which detectability is starting to decline for a species. Also, as highlighted by this study, dif-

ferent species may need different cut-off values for grouped data.

Right-truncation of the data generally had a rather small effect on the density estimates. This means that in a field situation it is more important for the observer to be careful about finding birds close to the transect and make good distance measurements to these, rather than to spend time finding and identifying individuals very far away.

In the case of species B the maximum distance of observation was 157 m and the distance between transect lines was 250 m. Thus it was sometimes possible for the same individual to be observed from more than one line. In theory this should not affect the density estimate as long as there is no double counting on the same line (Buckland et al. 2001). However, there is a chance that the confidence intervals around the estimates are slightly underestimated due to presence of dependent data points (pseudo replication).

Another simulation assessment analysis performed by Cassey & McArdle (1999) also validated the use of the Distance software for analysis of distance sampling data as long as the critical assumptions for such analysis were not violated. They also emphasised the importance of a carefully designed survey protocol and proper stratification and sampling of the study area to avoid biases in parameter estimates.

In conclusion this study has shown that density estimation using distance sampling along line transects generally performs very well as long as critical assumptions of the model are met. Both exact distance measurements and distance data grouped into discrete categories were useful for density estimations. Even if data were collected using only two categories (close or far away), the analyses produced reasonable estimates of true densities of birds. Such simple distance sampling is applicable to a large range of bird surveys and would prove valuable when analysing and evaluating the data. It is worth noting that this is a simulation study and that many practical issues arise when distance sampling is performed in the field (see Introduction). For example in this study, all distances between the transect and the bird was measured without error (an important assumption of the analysis model) but this may be very difficult to accomplish in a field situation. Proper training of the field workers is essential to minimise such errors during a real survey (Buckland et al. 2001).

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Sammanfattning

Genom att mäta avstånden till de observerade fåglarna under en inventering kan insamlade data användas för att räkna ut täthet och totalt individantal i det inventerade området (avståndsanalys). Med hjälp av avståndsdata räknar man först ut hur stor sannolikhet man har att upptäcka en individ av den aktuella arten vid ett visst avstånd. Med hjälp av denna sannolikhet kan man sedan räkna ut ett absolut mått på individtäthet och antalet individer i det inventerade området. Man kan således alltså ta hänsyn till de individer som inte observerats under inventeringen men ändå finns i studieområdet. Analysmetoden går att använda vid både punkt- och linjeinventeringar. Avstånden kan antingen mätas exakt eller uppskattas i två eller flera avståndskategorier (Figur 1).

När man samlar in avståndsdata är det väldigt viktigt att vara noggrann. Metoden att samla in inte bara antal fåglar av varje art, utan även avståndet till varje individ, är ganska arbetsintensiv. För att få tillräckligt bra data för att kunna analysera krävs oftast att man först tränat tillräckligt på metoden och har stor erfarenhet av fågelinventeringar. Det finns ett antal antaganden man gör när man analyserar avståndsdata och slarvigt fältarbete medför ofta att ett eller flera av dessa antaganden inte uppfylls. De viktigaste antagandena för avståndsanalys är:

1) *Avstånden är korrekt mätta.* Det är viktigt att man är mycket noggrann när man mäter avståndet till den plats där fågeln upptäcktes. Observera att det, när det är fråga om linjeinventeringar, är det kortaste avståndet mellan fågeln och linjen (alltså avståndet vinkelrätt från linjen) som skall användas. Det finns flera olika sätt att få fram detta avstånd (Figur 1). Antingen noterar man den plats där man först upptäckt fågeln och mäter avståndet dit först när man kommit fram så långt att man befinner sig mitt för punkten. Man kan också mäta det exakta avståndet från den plats där man befinner sig till fågeln samt vinkeln till linjen och sedan med hjälp av trigonometri räkna ut det rätvinkliga avståndet. En annan möjlighet är att man på en karta prickar in exakt var man upptäckte fågeln och sedan mäter avståndet i efterhand. Exakta avstånd mäts lämpligen med någon form av lasermätare. Om man inte har möjlighet att mäta exakta avstånd går det också att bara bedöma avstånden i två eller flera intervall (exempelvis 0–10 m, 10–25 m, 25–50 m, 50–100 m och över 100 m).

2) *Linjer eller punkter utgör ett representativt urval av den inventerade ytan.* För att linjerna el-

ler punkterna skall utgöra ett statistiskt representativt stickprov av den totala inventerade ytan är det viktigt att dessa är slumpmässigt eller systematiskt utplacerade i studieområdet. Om detta inte är uppfyllt kan man bara dra slutsatser om fågeltätheten kring linjerna och inte uppskatta det totala antalet individer i studieområdet.

3) *Fågeln har inte rört sig innan upptäckt.* Det är viktigt att fågeln inte hunnit röra sig i förhållande till observatören innan den upptäcks. Om fågeln till exempel hinner fly bort en bit från observatören innan upptäckt kommer man att notera ett för stort avstånd till fågeln och därigenom blir också tätheten och antalet individer i studieområdet över-skattat.

4) *Fåglar på linjen upptäcks alltid.* För att på ett säkert sätt kunna räkna ut sannolikheter för att upptäcka individer av en viss art vid ett visst avstånd ("upptäckbarhetsfunktion") är det viktigt att man upptäcker alla individer som befinner sig på (eller rakt ovanför) linjen eller punkten. Det är även bra om funktionen får en så kallad "skuldra", dvs att även en stor andel av de individer som befinner sig nära linjen upptäcks.

5) *Arten är korrekt identifierad för alla individer.* Det är viktigt att ha tillräcklig artkunskap om den eller de arter som skall inventeras för att säkert kunna identifiera de individer som observeras. Om man är osäker på artbestämningen av någon enstaka individ är det bättre att utelämna den observationen helt än att gissa vilken art det är.

6) *Tillräckligt stort antal observationer.* För att kunna göra en rimlig uppskattning av upptäckbarhetsfunktionen och därigenom erhålla ett bra mått på individtäthet är det viktigt att ha tillräckligt många observationer. Som en tumregel bör antalet observationer inte understiga 60.

Denna studie syftade till att utvärdera avståndsdata för att beräkna absoluta tätheter och antal individer i ett studieområde. Jag har själv kunnat se till att samtliga ovan nämnda kriterier varit uppfyllda tack vare att jag arbetat med simulerade data. Jag simulerade en inventering av två påhittade fågelarter (A och B), med olika täthet och lätthet att upptäcka. För att utvärdera analyserna jämförde jag de beräknade täthetsvärdena med de kända sanna tätheterna i området. Det påhittade studieområdet var 5 km² stort och i området hade 20 inventeringslinjer lagts ut enligt ett systematiskt mönster med slumpmässig startpunkt. Linjerna låg 250 m ifrån varandra och var 1 km långa. Varje linje inventerades en gång och avståndet från linjen till alla sjungande hanar av arterna A och B noterades.

Totalt observerades 70 hanar av arten A (i ge-

nomsnitt 3,5 per linje) och 69 hanar av arten B (i genomsnitt 3,45 per linje, Figur 2). Enligt den bästa versionen av avståndsanalysen fanns totalt 186 sjungande hanar av arten A i studieområdet (täthet: 37.2 hanar per km²). Detta värde ligger mycket nära det verkliga antalet som var 185 sjungande hanar. För art B uppskattades antalet sjungande hanar i området till 71 (täthet: 14.2 hanar per km²), medan det verkliga antalet var 66.

På det hela taget visade det sig således att de beräknade värdena låg mycket nära de sanna tätheterna för båda arterna (Tabell 1). Konfidensintervallen runt uppskattningarna inneslöt i samtliga fall de sanna värdena. Uppskattningarna var också relativt robusta mot olika typer av modifieringar av

data, såsom utelämnande av observationer gjorda på väldigt stora avstånd (högerkapning) och gruppering av avstånden i diskreta kategorier. När analyserna gjordes med avstånden indelade i bara två kategorier blev dock uppskattningarna osäkrare (större konfidensintervall).

Så länge de kritiska antagandena för avståndsanalys uppfylls under planering och fältarbete visar denna studie att avståndsdata kan användas för att göra goda skattningar av individtätheter i olika typer av fågelinventeringar. I de fall då det inte är praktiskt genomförbart att mäta exakta avstånd med tillräcklig noggrannhet, rekommenderas det att i stället uppskatta avstånden i två eller fler diskreta avståndsklasser.