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RESEARCH ARTICLE

A new double observer-based census framework to improve abundance estimations in mountain ungulates and other gregarious species with a reduced effort

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Abstract

1. Estimating animal abundance has a key role to play in ecology and conservation, but survey methods are always challenged by imperfect detection. Among the techniques applied to deal with this issue, Double Observer (DO) is increasing in popularity due to its cost-effectiveness. However, the effort of using DO for surveying large territories can be significant. A DO-based survey method that allows accurate abundance estimations with reduced effort would increase the applicability of the method. This would have positive effects on the conservation of species which are challenging to survey such as mountain ungulates.
2. We used computer simulations based on real data and a field test to assess the reliability of the DO and of a new proposed survey procedure, the Double Observer Adjusted Survey (DOAS). DOAS is based on total block counts adjusted with some DO surveys conducted in a proportion of the total area only. Such DO surveys are then used to estimate detection probability with a mark-recapture-derived approach.
3. We found that full DO is much more accurate than simple block counts for abundance estimations. DOAS is a less demanding alternative to full DO and can produce comparable abundance estimates, at the cost of a slightly lower precision. However, in the DOAS overall detectability has to be estimated within a sufficient number of sites (around a quarter of the total) to obtain a higher precision and avoid large overestimations.
4. *Practical implications*. DO methods could increase the reliability of abundance estimations in mountain ungulates and other gregarious species. Full DO in particular could allow researchers to obtain unbiased estimations with high precision and its usage is therefore suggested instead of block counts in wildlife monitoring. Given the high costs of full DO, the DOAS procedure could be a viable and cost-effective survey strategy to improve abundance estimates when resources are scarce.

KEYWORDS
abundance estimation, Alpine ibex, census effort, census methods, DOAS, double observer, double observer adjusted survey, mountain ungulates

1 | INTRODUCTION

Monitoring population abundance plays a crucial role in conservation as one strategy to understand drivers of population dynamics (Mignatti et al., 2012) or to assess the conservation status of a species (Toïgo et al., 2020). An important source of error in abundance estimations is imperfect detection (Kellner & Swihart, 2014; Lahoz-Monfort et al., 2014; Yoccoz et al., 2001), that is, the fact that some individuals can be missed during the observation. Individuals can be overlooked even by experienced operators, for example, because of weather conditions or rough terrain (Conway & Gibbs, 2011; Zabransky et al., 2016). Therefore, detectability (i.e. the proportion of individuals detected over the total of present individuals) is usually lower than 1. Several survey methods have been developed to account for imperfect detection, such as distance sampling (Buckland et al., 2001), Mark-Resight (Schwarz & Seber, 1999), and double observer (DO; Forsyth & Hickling, 1997). These methods perform differently under different field conditions and their applicability should be evaluated on a case-to-case basis (Schwarz & Seber, 1999; Seber, 1992; Sutherland, 2006).

For species living in mountainous environments, estimating abundance can be challenging due to potentially difficult terrain and the associated practical logistics (Singh & Milner-Gulland, 2011). Total block counts (hereafter also called block counts) are a ground-based monitoring strategy used to estimate abundance in many species (e.g. Brambilla, Von Hardenberg, et al., 2020; Jacobson et al., 2004; Largo et al., 2008). During block counts several observers count the number of animals simultaneously in each of the 'blocks', or sectors, of the study area. As they are based on a single repetition, however, block counts do not account for imperfect detection, leading to a possible underestimation of the population size (De Danieli & Sarasa, 2015; Loison et al., 2006; Morellet et al., 2007) of up to 50% (Gaillard et al., 2003; Wingard et al., 2011). Moreover, given the impossibility of estimating precision from a single census repetition, block counts are less suitable for long-term monitoring of population changes compared with statistically based sampling designs, even if these designs result sometimes in inaccurate abundance estimates (Cochran, 1977).

On the other hand, common methods that deal with imperfect detection such as distance sampling and mark-resight are challenging to apply to mountain species. Distance sampling requires assumptions that are difficult to meet in Alpine landscapes (Singh & Milner-Gulland, 2011) due, for instance, to the difficulty of correctly measuring distances. Distance sampling was indeed proved to be imprecise for Alpine chamois, *Rupicapra rupicapra* (Corlatti et al., 2015) and argali, *Ovis ammon* (Wingard et al., 2011). Mark-resight appears to be a robust method of abundance estimation for mountain ungulates (Corlatti et al., 2015; Fattorini et al., 2007; Largo et al., 2008; Neal et al., 1993) but it is costly to apply as individuals need to be captured for marking and it requires a significant number of resighting occasions (Otis et al., 1978; Schwarz & Seber, 1999).

The DO is a survey method that allows for the estimation of detection probability with a cost-effective survey design (Caughley, 1974; Magnusson et al., 1978). The method is based on two observers independently counting animals or groups of animals at the same time and the count data are subsequently compared with a Lincoln-Petersen-like approach (Forsyth & Hickling, 1997; Sutherland, 2006). This method allows a mark-resight analysis without the need to mark individuals, with only a single visit to each location, and is relatively easy to perform in the field. The DO is particularly suitable for gregarious species and is increasing in popularity for the monitoring of mountain ungulates (Ghoddousi et al., 2019; Khanyari et al., 2021; Michel et al., 2015; Suryawanshi et al., 2020; Tumursukh et al., 2016). Although it is easy to carry out and cost-effective compared with other methods, using the DO can still be unaffordable, in particular when the survey area is large as it requires a substantial number of observers (Suryawanshi et al., 2020) or helicopter surveys (Griffin et al., 2013). Consequently, the DO method is generally performed only in relatively small areas (e.g. Suryawanshi et al., 2012). Reducing the effort needed for DO surveys would therefore be fundamental to allow accurate counts in complex environments such as alpine areas. Unbiased estimation of population size would in turn largely contribute to conservation efforts in mountain ungulates, a taxon that includes many threatened species (IUCN, 2022a; Shackleton & IUCN/SSC Caprinae Specialist Group, 1997) and for which precise abundance data are often lacking (e.g. Brambilla, Von Hardenberg, et al., 2020; Gebremedhin et al., 2010; Harris et al., 2022; Shasha et al., 2020).

In this study, we test the robustness of the DO method in different field conditions (Aim 1). We also propose and test a new abundance estimation framework, the double observer adjusted survey (DOAS), that can reduce the survey effort needed to perform a full DO (Aim 2). The method is based on DO surveys being performed in only a portion of the total target area to estimate the detection probability. This is then used to adjust the counts obtained with total block counts conducted in the whole area.

To test DO and DOAS methods (Aims 1 and 2), we carried out simulated surveys on populations randomly built under real-case parameters, using as a case study the population of Alpine ibex (*Capra ibex*) in Gran Paradiso National Park (GPNP, Italy). Using these simulated surveys, we tested whether DO conducted in the entire area (full DO) and DOAS are able to provide reliable abundance estimates, compared with block counts, and the relative costs of the two DO methods. Moreover, we analysed factors that can influence the proportion of individuals estimated with full DO and DOAS, including abundance, group size, and detection probability.

To furtherly test our proposed DOAS method (Aim 2), we performed a field test with real census data in GPNP.

2 | MATERIALS AND METHODS

2.1 | Study system

The Alpine ibex is a mountain ungulate endemic to the European Alps that inhabits high-altitude alpine meadows and rocky slopes (Brambilla, Bassano, et al., 2020). The species is characterized by a high level of sexual dimorphism. Adult males can weigh twice as much as females (Couturier, 1962; Michallet, 1989) and have larger horns (Michallet et al., 1994), making the sexes easily recognizable. The exact age of the individuals can be assessed by counting annual growth rings on the horn (Brambilla & Canedoli, 2013; Toïgo et al., 2013). The age class of a male can be distinguished at a distance using a combination of body and horn size.

The population of Alpine ibex in GPNP has been estimated since 1957 by yearly block counts and ranges from ~2600 to ~5000 (with an average of ~3400 individuals; Jacobson et al., 2004, Mignatti et al., 2012).

2.2 | DO method and DOAS procedure

The DO is a census method that requires that two observers independently count groups of animals along ground transects using trails and/or vantage points while ensuring they are visually covering as much of the target area as possible. The method relies on several assumptions, reviewed by Suryawanshi et al. (2012). In particular, the detected groups of animals should be individually identifiable by the observers, for example by their position, group size, age–sex composition, or the presence of individuals with distinctive traits (Otis et al., 1978; Seber, 1982). Furthermore, the study population should be closed for the entire duration of the survey.

To ensure the independence of the two counts (Magnusson et al., 1978), the two observers survey the same area at an optimal distance, large enough that they do not cue each other as to the location of the animals but short enough to ensure the groups' composition remains constant (Suryawanshi et al., 2012). In previous applications of the DO on mountain ungulates, the two operators started the surveys with a 15–60 min delay (e.g. Suryawanshi et al., 2020; Thapa et al., 2021), but spacing should be considered on a case-by-case basis.

At the end of the survey procedure the observed groups are compared with identify those detected by one of the observers or by both. The actual number of groups present in the area is estimated with Equation (1) by Forsyth and Hickling (1997), derived from the Lincoln-Petersen approach in the capture-mark-recapture framework, but conducted on groups rather than on single individuals:

$$G_{est} = \frac{(B + S_1 + 1)(B + S_2 + 1)}{B + 1} - 1, \quad (1)$$

where G_{est} = estimated number of groups, B = groups seen by both observers, S_1 = groups detected only by observer 1, S_2 = groups detected only by observer 2.

Group detectability (p) is estimated for each observer as the number of groups detected (G_{det}) divided by the number of groups estimated:

$$p = G_{det} / G_{est}. \quad (2)$$

Estimated population (N_{est}) is given by the estimated number of groups (G_{est}) multiplied by the estimated mean group size (S_{est}), calculated as the average size of all groups observed (Forsyth & Hickling, 1997; Suryawanshi et al., 2020):

$$N_{est} = G_{est} \times S_{est}. \quad (3)$$

Our proposed survey framework, the DOAS is based on the DO method but DO counts are only performed in some sectors (i.e. portions of the target area), while the entire area is monitored with block counts. The detection probabilities in each sector are estimated through Equation (2) and then are averaged between all sectors surveyed with the DO. This allows an estimate of detectability in the whole area, which is then used to adjust the abundance obtained with block counts. More details on the method are provided in the following sections and in Appendix S1.

2.3 | Alpine ibex populations simulations

We built simulated populations of Alpine ibex in GPNP using real-case parameters (Table 1). Each population had an abundance that was classified as either low, medium or high based on the recorded counts of Alpine ibex in GPNP (Jacobson et al., 2004). The GPNP area is divided into 38 sectors that are traditionally used during surveys. A sector usually includes one or more side valleys and is under the responsibility of one or two park rangers. Individual animals were split at random into the 38 sectors (or subareas). The average number of individuals assigned to each sector was proportional to the average number of individuals counted with block counts in that subarea over 20 years (from 2000 to 2020). In each sector, individuals were further split into a random number of groups with an assigned mean size, simulating the unpredictable grouping of the animals in the real-case surveys. More details on the simulation process are provided in Appendix S1.

2.4 | Block counts and DO methods simulations

To both test, the robustness of the DO method in different conditions (Aim 1) and validate our proposed DOAS procedure (Aim 2), we conducted simulated surveys on the Alpine ibex populations built as indicated in the previous paragraph. On each randomly generated population we performed: (a) block counts (performed by a single observer), where only the animals observed in the single survey repetition are counted, (b) DO performed in the entire area (full DO), (c)

TABLE 1 List of parameters used in the surveys simulations.

Parameter	Meaning	No. of values	Possible values
λ	Expected population size	3	2500, 3500, 5000
K	Mean expected group size	3	5, 10, 15
p	Group detection probability	7	0.3, 0.4, 0.5,0.6, 0.7, 0.8, 0.9
cf (correction factor)	Detectability of a single individual compared with that of a large group (15 individuals or more)	3	0.3, 0.5, 0.7
U	Miscount effect: mean ratio of group size estimated compared with actual group size (proportion)	3	1, 0.9, 0.8
Sdp	Variability of detection probability between sites (standard deviation)	3	0.1, 0.3, 0.5
Obs	Observer effect: Mean ratio of detection probability for obs. 2 compared with obs. 1	3	1, 0.75, 0.5
n	Number of sites surveyed with double observer for the double observer adjusted survey	37	1 to 37

our proposed DOAS procedure (block counts in the entire area, with additional DO performed only in some sectors).

Simulated surveys were performed under different scenarios of detectability, assigning in each simulation a value of p, the overall group detection probability (i.e., the probability for a group to be detected by the observers), that ranged from 0.3 to 0.9, with a bin size of 0.1. Heterogeneity in detection probability could be a major problem in abundance estimations with mark-recapture approaches (Laake & Collier, 2023). Therefore, in our simulations, detectability was allowed to vary between sectors, with the actual group detection probability in each sector randomly generated around the assigned value of p (and a standard deviation of either 0.1, 0.3, or 0.5). Detection probabilities also varied between the two observers, simulating operators with different experiences and/or environmental conditions (detectability of the second observer was either 0.5, 0.75, or 1 times that of the first observer). All the values of the parameters used in the simulations are arbitrary but are meant to represent situations with respectively low, medium, or high effects of such factors, based on previous field observations in GPNP.

We also accounted for possible miscounts of group size (Clement et al., 2017; Cogan & Diefenbach, 1998) and for the fact that small groups are more difficult to detect than large groups. To deal with possible miscounts, the mean group size observed in the simulated surveys (and used to calculate the total number of individuals with equation 3) was randomly generated around the true mean size of the detected groups (simulating no overall miscount) or around 90% or 80% of the true mean size (simulating an overall undercount). A miscount of 0.88–0.96 of the true abundance was for instance found for elk living in an open landscape (Cogan & Diefenbach, 1998). Moreover, the detection probability of each group increased with group size, simulating a real-case scenario in which groups of few individuals are more difficult to detect than large groups (Graham & Bell, 1989; Samuel et al., 1987; Schlossberg et al., 2018). We considered that groups larger than a certain size (i.e., 15 individuals in our simulations) all had the highest probability of being detected, while the detectability was lower for smaller groups. In particular, we assigned the detectability of a single individual to be 0.3, 0.5, or 0.7 times that of a large group, and the group size effect to be stronger with few individuals (for instance the difference in detectability between groups of 1 or 2 individuals was higher than that between groups of 14 and 15 animals), as shown for example by Schlossberg et al. (2018).

During the counts with each of the three methods (block counts, full DO, and DOAS) groups were detected or not detected given the detectability obtained with the criteria presented in this paragraph.

Further details on the simulated survey procedure and the mathematical formulations are provided in Appendix S1.

2.5 | Test of full DO and DOAS reliability

To answer the main aims of our study, we tested the bias and precision of DO methods (full DO and DOAS) compared with block counts. In each survey, we assessed the ratio of estimated individuals compared with the true assigned abundance, and in particular:

a. For the block counts, we obtained the block count ratio (R_{block}) by dividing the total number of individuals counted in the entire area by the known simulated abundance.
b. For full DO surveys, two separate censuses were conducted in each sector by two different observers. Data were entered in a group observation matrix: 1 was assigned to groups detected by each observer and 0 to missed groups. Therefore, the matrix

contained 1–1 if a group was detected by both observers, 1–0 if it was only seen by observer 1 and 0–1 if it was only seen by observer 2. The expected number of groups in each sector was estimated with equation (1) and the estimated abundance calculated with Equation (3). The DO ratio (R_{DO}) was calculated as the total estimated abundance (i.e. the sum of the 38 sectors), divided by the known simulated abundance.

c. For the DOAS, block counts were first ran in the entire area. We then selected in each simulation only a sample of sectors (1–37 sectors), using them to perform the DO surveys. A group observation matrix as described before was built for each DO survey, and the group detection probability for each observer was estimated with Equations (1 and 2). The average of all the detection probabilities estimated in each sector was the estimate for the group detection probability in the whole area (P_{est}). This value was then used to adjust the data of the block counts, wherein each of the 38 sectors the adjusted number of groups (G_{adj}) was simply given by:

$$G_{adj} = G_{count} / P_{est}, \quad (4)$$

where G_{count} was the number of groups detected during the block counts in that sector. The adjusted number of individuals (N_{adj}) in each sector was therefore:

$$N_{adj} = G_{adj} \times S_{count}, \quad (5)$$

where S_{count} was the average group size observed during block counts in that sector.

In our DOAS simulations, block counts and DO were assumed to be performed on different occasions, thus the groups' composition and group detectability changed randomly between the two survey methods, following the criteria presented in the previous paragraph and in Appendix S1.

After the DOAS surveys, the DOAS ratio (R_{DOAS}) was calculated as the total estimated individuals (either N_{tot} or the sum of N_{adj} of the 38 sectors) divided by the known simulated abundance.

For DO and DOAS methods we classified as overestimations all the simulations in which the estimated abundance was at least 20% higher than the simulated abundance (or ratio higher than 1.2).

To further analyse the reliability of DO and DOAS methods under different conditions, we tested the effect of the parameters included in the simulations (Table 2) on the ratios of estimated individuals (R_{block}, R_{DO}, R_{DOAS}). We built linear mixed models with different combinations of target parameters as fixed factors and the number of surveyed sectors as a random factor. We selected the best models as the ones with the lowest Akaike information criterion (Akaike, 1974).

TABLE 2 Model selection for the effect of the tested parameters on the ratio of individuals estimated with the two survey methods: Full DO (R_{DO}) and DOAS (R_{DOAS}). We ran all the univariate models ($N = 8$, see Table 1 for the list of all parameters considered) and a series of multivariate models with a biologically plausible combination of the parameters, for a total of 25 models for each survey method. For the best model only ($\Delta AIC = 0$), highlighted in bold, we provide the model outcome with the estimated direction of the effect of the parameters (positive or negative) and the 95% CI.

Survey method	Model	AIC	ΔAIC	Parameter	Effect	Estimate 95 CI
Full DO	~p	−1619	1047			
	~sdp	−2174	492			
	~K + U + obs	−2199	467			
	~p + sdp	−2342	324			
	~p + K + U + obs + sdp	**−2666**	**0**	intercept	+	[0.021, 0.021]
				group det.p (*p*)	+	[0.418, 0.419]
				avg. group size (*K*)	−	[−0.011, −0.010]
				avg. miscount (*U*)	+	[0.792, 0.796]
				obs. error (obs)	+	[0.191, 0.193]
				p variability (sdp)	−	[−0.218, −0.216]
DOAS	~λ	3143	230			
	~n	3131	218			
	~p + sdp + λ	3102	189			
	~p + sdp + U	2925	12			
	~p + K + U + obs + sdp	**2913**	**0**	intercept	+	[0.062. 0.067]
				group det.p (*p*)	+	[0.476, 0.478]
				avg. group size (*K*)	−	[−0.007, −0.006]
				avg. miscount (*U*)	+	[0.911, 0.916]
				obs. error (obs)	−	[−0.292, −0.289]
				p variability (sdp)	−	[−0.208, −0.206]

Abbreviations: AIC, Akaike information criterion; DO, double observer; DOAS, double observer adjusted survey.

Finally, to compare the costs of the three survey methods (block counts, full DO, and DOAS), we calculated for each the number of effort units (or e.u.) required to perform the census. An effort unit was defined here as the time needed by one operator to entirely survey a single target sector. In the real-case scenario and given the area of each sector (5.2–37.2 km^2), an effort unit for Alpine ibex censuses in GPNP corresponds to two full days of transects.

All the population and survey simulations described here, as well as all the statistical models, were performed in R version 4.3.1 (R Core Team, 2022). The full script is provided in Appendix S3.

2.6 | Field test

Finally, we tested the DOAS method with real data performing a field study in GPNP to estimate the abundance of the local Alpine ibex population. GPNP covers an area of 720 km^2, entirely on mountainous terrain (with a range of 700 to 4000 m a.s.l.). Therefore, performing a full DO in the Park would imply high costs and technical constraints.

Block counts were performed by Park rangers at the beginning of September 2022. Each ranger performed the counts in a single assigned sector, covering an area of 10–30 km^2 over two consecutive days. The abundance estimated with block counts was obtained by the sum of the individuals seen by each operator in his sector. In addition, 10 DO sessions were performed in different sample sectors over the Park during July and August 2022, involving 19 different observers. Animals were counted using binoculars and spotting scopes. The observers were divided into two groups with the second group starting 10–20 min after the first group. We have observed previously that the composition of ibex groups remains relatively constant over a 20 min period (M. Panaccio & A. Brambilla, *personal observation*). We then applied the DOAS procedure, estimating the overall detection probability as the average of the 10 DO repeats and adjusting the block counts data accordingly. To test the robustness of the abundance estimated with the DOAS, we also applied the method to a subset of sectors counted with the DO (3–9 randomly selected samples).

3 | RESULTS

3.1 | Full DO and DOAS reliability

We ran 18,881,100 simulations using different combinations of target parameters (total population size, mean group size, group detection probability, variability of detectability, observer's effect, miscount effect, extent of size miscounts, and number of sites used for the DOAS). All the possible values of the parameters are presented in Table 1.

The overall accuracy of each survey method is represented in Figure 1, while in Figure 2 accuracy is linked to the overall assigned detectability.

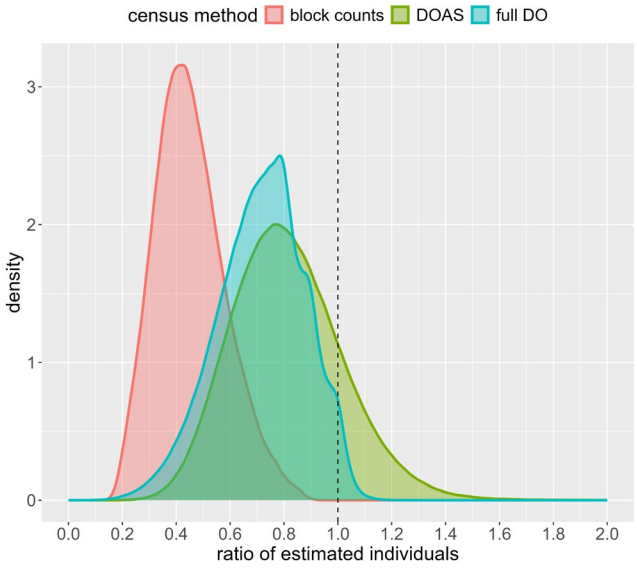

FIGURE 1 Overall ratio of individuals estimated in the estimations for each survey method, with all the combinations of the eight considered parameters. The ratio was calculated as the estimated abundance divided by the true simulated number of individuals. The dotted vertical line represents the true simulated abundance. DO, double observer; DOAS, double observer adjusted survey.

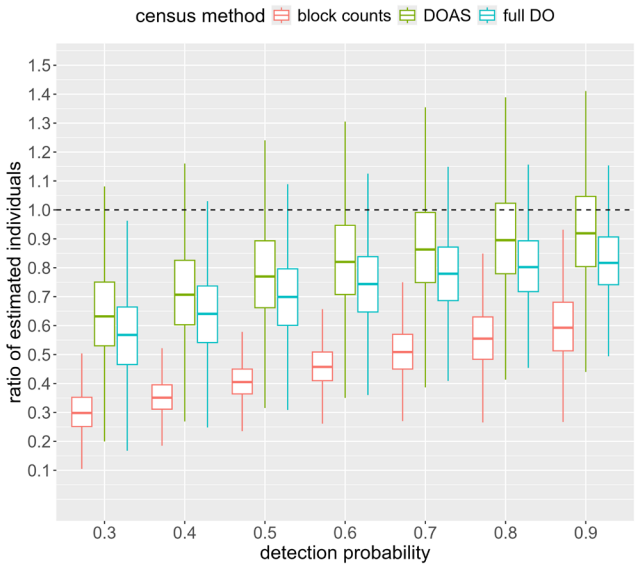

FIGURE 2 Average accuracy of the three different survey methods for each overall detection probability of the groups assigned in the simulations. Accuracy is given by the ratio of estimated abundance compared with true simulated abundance in each simulation. In this graph, outliers were removed. DO, double observer; DOAS, double observer adjusted survey.

Under the various scenarios of detectability block counts estimated on average only a proportion of 0.453 ± 0.129 of the actual population. To perform full block counts, we calculated a cost of 38 effort units (one for each of the 38 sectors, that has to be sampled once by one operator).

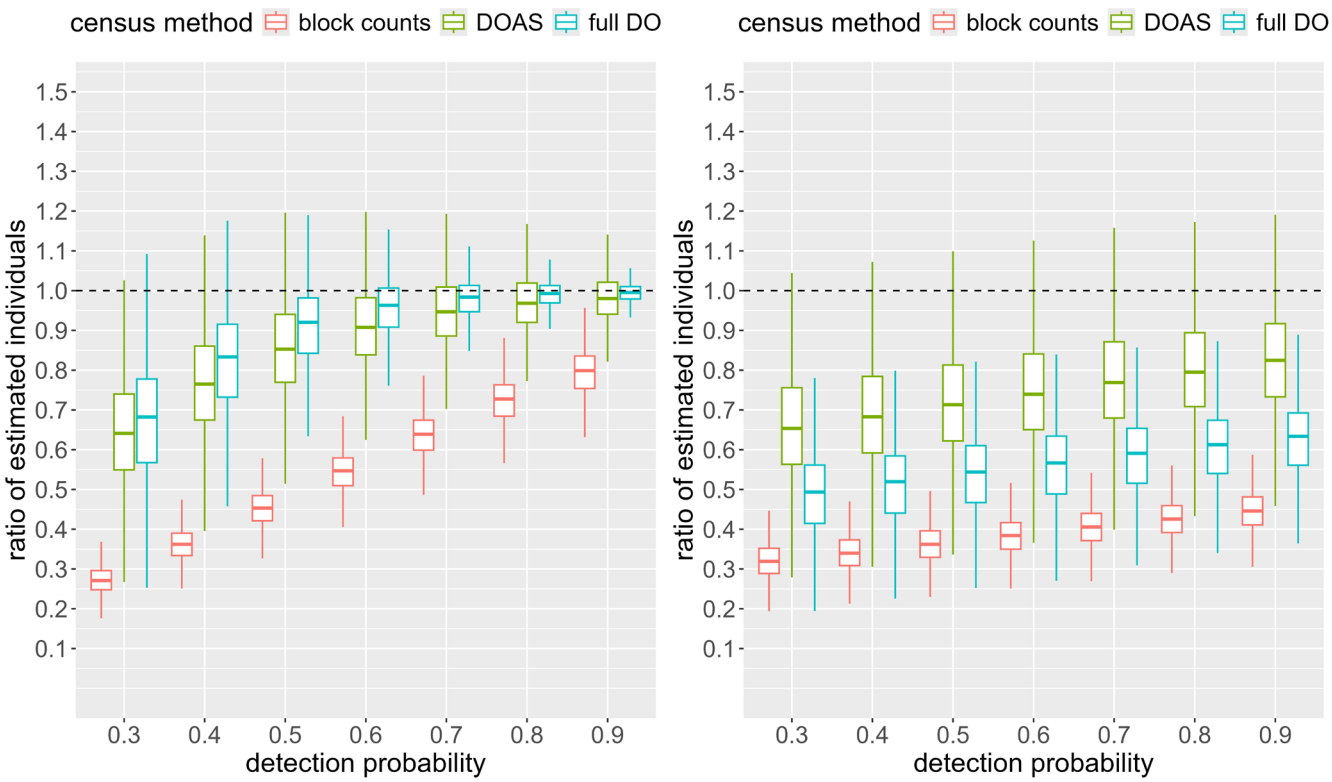

FIGURE 3 Accuracy of the three survey methods for each detection probability, but under different combinations of census parameters. On the left, the most favourable survey scenario with the lowest variability of detection probability (sdp = 0.1), the same observers' ability (obs = 1), and no miscounts of the group size ($U = 1$). On the right, the opposite situation with the highest variation of detectability between sectors (sdp = 0.5), overall undercounts of group size ($U = 0.8$), and observers of different abilities (obs = 0.5). DO, double observer; DOAS, double observer adjusted survey.

Full DO surveys were able to estimate a ratio of 0.715 ± 0.163 of the simulated abundance. Even with a very low detectability (0.3), DO estimated around 0.6 of the real population. To perform full DO, we calculated a cost of 72 effort units (2 for each of the 38 sectors, where each sector has to be sampled once but with two operators).

The DOAS method showed an average ratio of estimated individuals of 0.821 ± 0.207 and the DOAS ratio was higher than the DO ratio for each value of detectability (Figure 2). However, the precision of the DOAS was lower and several cases of very high overestimation were present. Indeed, R_{DOAS} range was 0–4.21 (above 1.2 in 4.24% of cases) while the range for R_{DO} was 0.04–1.37 (above 1.2 in 0.003% of the cases) and for R_{count} was 0.11–0.96.

The accuracy of the full DO increased with lower group size, higher precision in estimation of group size, lower variability of detectability across sectors, and higher similarity of detectability between the two observers (Table 2; see Appendix S2 for further information). DOAS performance was also linked to the same factors (Table 2). R_{DOAS} increased with lower group size, higher precision in estimation of group size, lower variability of detectability across sites, and lower similarity of detectability between the two observers, with no effect of population size and of the miscount effect on detectability.

Under the most favourable census conditions, characterized by low variability in detectability, unbiased estimation of group size, and observers of similar ability, abundance estimations from full DO and DOAS both produced similar values on average, although full DO had a higher precision (Figure 3). Nevertheless, under the worst census scenario (highest variability in detectability and large miscounts), DOAS estimated a higher proportion of the actual abundance (Figure 3).

The number of DO surveys performed to estimate detection probability (considering the number of surveyed sectors) was not a significant factor in the R_{DOAS} model. However, the mean DOAS ratio became constant only when DO surveys were performed in 10 or more different sectors (Figure 4). Similarly, the proportion of overestimations (R_{DOAS} higher than 1.2) was lower than 1% only when using 10 or more sectors to estimate detectability. Overestimations were more frequent with less DO samples (Figure 4).

If the DOAS is performed using total block counts and DO counts in 10 sectors, the costs required to perform the method would be 58 effort units (38 for the block counts and 20 for the DOs, 2 for each of the 10 sectors). This effort is 53% higher than block counts but 20% lower than a full DO (Table 3).

3.2 | Field test

In the 10 DO surveys performed in GPNP, we found a detectability (average ± standard deviation) for the individuals of 0.781 ± 0.101 (95% confidence interval: [0.709–0.853]). This led to an estimation of 3471 ± 500 Alpine ibex (95% CI: [3150–3791]) obtained with the DOAS, compared with 2687 ibex estimated with block counts. The estimated group detectability was very similar (mean: 0.777 ± 0.092, 95% CI: [0.712–0.843]). The mean group size observed comprised 6.52 ± 6.02 individuals.

We selected random groups of n DO surveys (with $3 \leq n \leq 9$) using these subsamples to perform the DOAS. The number of sites sampled with DO did not change the outcome of abundance estimations (one-way ANOVA, $F(6, 343) = 1.168$, $p = 0.323$) and DOAS was therefore unbiased even with a low number of sectors sampled with DO. However, increasing the number of DO repeats also increased the precision of the method, reducing the range of the estimates (Figure 5).

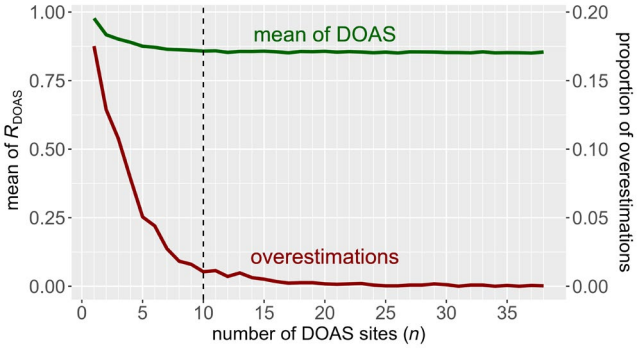

FIGURE 4 Average ratio of individuals estimated with the DOAS (green line) and proportion of overestimations (red line) obtained with the method, depending on the number of sectors surveyed with DO (*n*) used to estimate the detection probability. A DOAS simulation was classified as overestimation if the estimated abundance was at least 20% higher than the true abundance. DO, double observer; DOAS, double observer adjusted survey.

4 | DISCUSSION

Our simulations showed that DO methods improved the abundance estimation of a population of wild ungulates.

Total block counts had a low accuracy and were able to estimate only a proportion of the total population. Performing a DO in the entire area (full DO) was more accurate than block counts, estimating almost twice the number of individuals in conditions of low detectability and reaching a high overall accuracy with high detectability, low bias, and high precision. The DOAS procedure, that involves total block counts in the entire area and additional DO surveys in a sample of sectors to estimate detectability, could produce abundance estimates comparable to the full DO with a lower survey effort but also a lower precision.

The overall DOAS ratio (i.e. estimated number of individuals compared with true total abundance) was unexpectedly higher than the full DO, estimating on average about 10% more individuals. However, this result is probably related to DOAS overestimations under specific combinations of parameters. With similar detectability between the observers, low variation in detection probability between sectors, and without miscounts of group size, DOAS, and full DO were indeed both unbiased and full DO had a higher precision. In contrast, under conditions of a high miscount of group size, high variation in detection probability, and different detectability between the observers, the DOAS ratio appeared to be higher. However, with such unfavourable census conditions, both the full DO and DOAS would yield inaccurate results, and the higher overall DOAS ratio would be simply caused by overestimations. Indeed, many cases of abundance estimates that were much higher than the actual population were found with the DOAS (with rare cases where the estimated abundance was up to four times higher than the real number of individuals), while they were very rare with the full DO. However, the proportion of DOAS overestimations shrank when at least 10 DO surveys were performed. In such cases, less than 1% of all simulations resulted in an overestimation higher than 20%.

Therefore, performing the DOAS in which less than 10 of the 38 sectors are surveyed with a DO would probably produce unprecise

TABLE 3 Comparison of the three survey methods analysed in this study, based on the simulations over the GPNP landscape. We compare for each method the reliability in abundance estimation, probability of overestimations, and costs (in terms of effort units, or e.u.). One effort unit is here defined as the time needed by one operator to entirely survey a single target sector (among the 38 in which GPNP is divided for the survey procedure).

Survey method	Abundance estimation	Overestimations	Costs	Usage in the field
Block counts	Biased (undercounts)	None	38 e.u.	Not advisable, use only if census resources are very scarce
Full DO	Generally unbiased with high precision	Very rare	72 e.u.	Suggested method for higher precision (see Section 4)
DOAS (10 sectors sampled with DO)	Generally unbiased with lower precision	Possible	54 e.u.	Suggested method to reduce costs (see Section 4)

Abbreviations: DO, double observer; DOAS, double observer adjusted survey; GPNP, Gran Paradiso National Park.

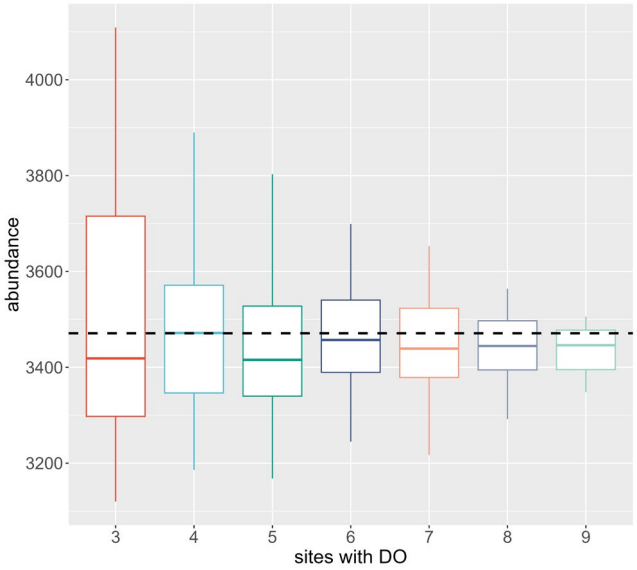

FIGURE 5 Population estimated with DOAS in the field test, using subsets of 10 surveyed sites (or sectors) to calculate detection probability. The dotted line represents the abundance estimated when all 10 sectors are surveyed with DO and used to estimate detectability. DO, double observer; DOAS, double observer adjusted survey.

abundance estimations and risk severe overestimations. In the simulated study area (that matches the conditions of GPNP) a sample of 10 sites out of the total 38 corresponds to 10%–40% of the total area. At the same time, in our study surveying more than 10 sample sectors would not have produced a significant increase in the precision of the method. In other areas, particularly those with more heterogeneous landscapes, the proportion of sectors requiring DO sampling may need to be higher than one-quarter of the total. Therefore, our results should be interpreted cautiously and adjusted on a case-by-case basis. Additionally, in areas with significant environmental variability between sectors, it is crucial to ensure that the sites chosen for DO surveys are representative of the entire target area. If not, the average detection probability might not accurately reflect the whole landscape, potentially leading to incorrect abundance estimates.

According to the results of the simulations, variability of detection probability between sectors and between observers was an important factor affecting the accuracy of DO methods. In our field study, the variation of the detection probability was low (0.101), despite the large number of different observers, probably allowing for a more precise abundance estimation. Besides, our overall estimated detection probability was higher than other studies on this species (Bison et al., 2019; Gaillard et al., 2003), probably because all counts were performed by expert park rangers who were familiar with the census area (Jacobson et al., 2004). However, the outcome of our simulations suggests that reliable results with the DOAS could have also been obtained with lower detection probabilities suggesting that DOAS could be a reliable survey method in areas where expert personnel are less available.

Group size and size undercounts were the other key factors affecting full DO and DOAS accuracy: accuracy increased if groups were small and group size was correctly estimated. In our field study, the average group size was low (6.52 individuals), which could have been another factor in reducing DOAS bias.

4.1 | Conservation implications of DO methods

DO methods could constitute an accurate survey strategy to monitor mountain ungulates, potentially offering more effective methods for managers that currently use block counts. Table 3 provides a comparison of the three methods, including reliability and costs.

Block counts remain a very common method to monitor mountain ungulates (e.g. Brambilla, Von Hardenberg, et al., 2020; Corlatti et al., 2022; Donini et al., 2021; Herrero et al., 2011), due to their comparatively low costs in large and rugged areas. However, block counts can be biased (Bison et al., 2019; De Danieli & Sarasa, 2015), and indeed in our simulations, the method estimated less than half of the individuals actually present, with the population being underestimated by 90% in some simulations. Researchers that currently perform block counts should therefore consider the possibility of using DO methods for monitoring purposes. In particular, due to its high accuracy and higher precision, full DO is the most advisable survey method if there are enough resources to cover its field costs, while DOAS is a comparable alternative to reduce the survey efforts.

The full DO method has already been applied to estimate the abundance of many species of mountain ungulates (Ali et al., 2019; Khattak et al., 2020; Leki et al., 2018; Thapa et al., 2021). The reliability of the DO method in detecting true abundance has still to be proven, since several sources of error and low detection accuracy have been identified previously with this method (Alldredge et al., 2008; Corlatti et al., 2017; Lubow & Ransom, 2016). Here we showed that performing a DO count in the entire target area generally produced an unbiased estimation of abundance with high precision suggesting the suitability of this method for estimating abundance in mountain ungulates.

On the other hand, DOAS could be considered an alternative method to the full DO to reduce monitoring costs. Indeed, the DOAS as proposed in this study, with around a quarter of the sectors sampled with a DO, would reduce the required field effort by around 20% compared with a full DO, and produce similar abundance estimates (at the cost of reduced precision and the risk of some overestimations). Effort reduction and financial sustainability are of key importance in the long-term monitoring of wildlife (Caughlan & Oakley, 2001).

In areas where mountain ungulates are already monitored with block counts, the DOAS method would only require additional DO surveys in approximately a quarter of the total sectors (10%–40% of the total area) to adjust data from block counts. Such a procedure would necessitate an increased effort (around 50% higher) but would also produce a noticeable improvement in abundance estimates and would remain less costly than changing the monitoring

procedure to a full DO. Furthermore, applying the DOAS would also not interrupt a historical series of block counts, which can be fundamental for continuity in studies of long-term population dynamics (Coulson et al., 2000; Imperio et al., 2010; Mignatti et al., 2012; Reynolds et al., 2011; White, 2019).

The increased DOAS costs could potentially be offset if a single operator acts as the two observers in the DO surveys, but this method requires further research before it can be reliably applied. Although conducting DO in less than a quarter of the sectors to estimate detectability would further reduce the effort of the DOAS, our results suggest against this since we have shown that this would reduce the precision of the method and increase the risk of large overestimations—both of which can be problematic when monitoring threatened species. For instance, the extinction risk of a species (a key conservation driver) is based on its abundance (IUCN, 2022b; Rueda-Cediel et al., 2018). Authorities commonly rely on abundance estimations to guide their conservation efforts (Armstrong & Seddon, 2008; Krausman & Bleich, 2013; Lkhagvasuren et al., 2016; Stüwe & Nievergelt, 1991) such as identifying management strategies, for example, hunting (Herrero et al., 2010). Overestimates in abundance could potentially result in erroneous management or conservation decisions.

The DO estimations have the potential to be used in any species (in addition to mountain ungulates) that live in groups in large areas. We indeed analysed a large range of variability for detection probability (between individuals, sites and observers). We included very low to very high detection probabilities based on a range of environmental conditions, species' characteristics or observation errors. However, in species with very large group sizes, the DO methods could be less effective. For example, undercounts usually increase with group size (Davis et al., 2022; Gerrodette et al., 2019; Graham & Bell, 1989). Undercounts of above 50% have been reported in species that live in large flocks, such as birds (Frederick et al., 2003), and such miscount values were not analysed in out simulations. However, since the accuracy of full DO and DOAS decreased with miscounts of group size, the method is likely to be imprecise with very large group sizes. Future research should explore modifications to the full DO and DOAS methods, hence they can obtain reliable population estimates across all group sizes.

AUTHOR CONTRIBUTIONS

Matteo Panaccio: Conceptualization (equal); formal analysis (lead); methodology (equal); writing—original draft (lead). Alice Brambilla: conceptualization (supporting); formal analysis (supporting); methodology (supporting); supervision (supporting); writing—review and editing (equal). Bruno Bassano: Conceptualization (supporting); supervision (supporting); writing—review and editing (supporting). Tessa Smith: Supervision (supporting); writing—review and editing (supporting). Achaz von Hardenberg: Conceptualization (equal); formal analysis (supporting); methodology (equal); supervision (lead); writing—review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest in this research.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Mathematical details of the simulations.

Appendix S2. Additional figures.

Appendix S3. R script for census simulations.

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