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METHODOLOGICAL INSIGHTS

Effects of radio-collar position and orientation on GPS radio-collar performance, and the implications of PDOP in data screening

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Summary

1. Global positioning system (GPS) radio-telemetry has become an important wildlife research technique worldwide. However, understanding, quantifying and managing error and bias in raw GPS radio-telemetry data sets requires much more work. In particular, error and bias resulting from position (angle away from vertical) and orientation (compass direction) of GPS radio-collars on free-ranging animals is currently unknown.
2. We tested the effects of collar position and orientation on GPS radio-collar performance using five stationary GPS radio-collars. We also investigated the use of positional dilution of precision (PDOP) as a method for screening data with high location errors.
3. Orientation had no statistical effect on fix rates or location errors. The biggest source of variation was attributed to collar position, which resulted in significantly lower performance at angles below 90° from vertical.
4. PDOP-based screening was effective and can be used to lower location error, but the trade-off between higher location accuracy and data loss (potentially leading to new bias) must be assessed.
5. *Synthesis and applications.* The results of this study refine our understanding of error and bias in GPS radio-telemetry data. We suggest that collar orientation can safely be disregarded, whereas radio-collar position remains a large potential source of error and bias. This finding has major implications regarding animal activity and GPS radio-telemetry research. Researchers need to quantify and account for biases resulting from animals moving through heterogeneous terrain and habitats.

Key-words: aspect, bias, fix rate, location error, PDOP, radio-telemetry

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Introduction

Global positioning system (GPS) radio-telemetry is a relatively new technology that has become an important wildlife research technique. The principal advantage of GPS radio-telemetry over more traditional methods, such as VHF radio-telemetry, is the consistent accrual of large numbers of locations per radio-collar (or animal) through automated tracking. While increasing the number of locations per animal results in higher accuracy of individual home range and habitat use parameter estimates (Otis & White 1999; Girard *et al*. 2002), researchers must address potential error and bias in raw GPS radio-telemetry data (Moen, Pastor & Cohen 2001; D'Eon *et al*. 2002; D'Eon 2003; Frair *et al*. 2004). With any new technology, rigorous testing must be a priority in order to ensure that accurate conclusions are reported, and GPS radio-telemetry is no exception.

Arguably, the largest source of potential error and bias in radio-telemetry data is likely to be associated with missing data (D'Eon 2003; Frair *et al*. 2004). Missing data occur when GPS radio-collars are set to acquire GPS locations (referred to as a 'fix') on a pre-defined schedule (for descriptions of GPS radio-telemetry and associated procedures, see Rodgers, Rempel & Abraham 1996; D'Eon *et al*. 2002) and < 100% of potential locations are in the database after collars are retrieved from free-ranging animals. Fix rates ≤ 50% on free-ranging

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animals have commonly been reported (Merrill *et al.* 1998; Obbard, Pond & Perera 1998; Dussault *et al.* 1999; D'Eon 2003) and may be the result of fix-rate biases. A fix-rate bias occurs if missing data are not randomly distributed, but rather the result of a directional bias caused by environmental factors. D'Eon (2003) demonstrated that, while direct effects of terrain and canopy closure account for some of the missing data, a large source (if not the largest) of missing data is related to unknown factors that may be related to the effects of animal activity in free-ranging environments.

One of the most important variables associated with the activity of a radio-collared animal is the position and orientation of the GPS antenna on radio-collars, and the ensuing effect on fix rates. Indeed, in two studies directly investigating the effects of animal activity on GPS radio-telemetry, both concluded that animal behaviour affected collar performance (Moen *et al.* 1996; Bowman *et al.* 2000); however, quantitative relationships and the means to address these effects remain elusive. Conventional wisdom expects that a vertically orientated radio-collar with an unobscured view of the sky will have the most success in obtaining GPS fixes and the lowest bias, because it will have the best satellite acquisition rate. However, the exact degree to which this bias increases with angle away from vertical and in combination with compass direction is unknown. Radio-collar position and orientation are critical factors related to animal activity, as it is movement and activity of free-ranging animals that will determine the position and orientation (and therefore bias) on deployed radio-collars in wildlife studies (Moen *et al.* 1996; Bowman *et al.* 2000). Bias related to animal activity will no doubt vary among species and perhaps even individuals. A collared animal that often digs while foraging (e.g. bear *Ursus* spp.; Obbard, Pond & Perera 1998) may have a different fix-rate success because of a different position and orientation (relative to the sky or horizon) of the radio-collar than an animal that keeps its head more horizontal while foraging (e.g. moose *Alces alces*; Moen *et al.* 1996), leading to differing bias in resultant radio-collar data.

A secondary source of error and bias in GPS radio-telemetry data is location error, which is the difference between the recorded location (i.e. collar data) and the true location. While uncorrected GPS radio-telemetry data have been demonstrated to be sufficient for many broad applications in wildlife research (±31 m 95% of the time; D'Eon *et al.* 2002), attaining a specific level of location accuracy could be desirable or necessary in some cases. Several studies have discussed the use of available surrogates of accuracy for screening raw GPS radio-telemetry data: location error may be unknown, but other potentially useful parameters are recorded by the radio-collar. These studies primarily focus on the use of dilution of precision (DOP; for description of GPS parameters see MELP 2001) and two-dimensional (2-D) vs. three-dimensional (3-D) fixes (Rempel, Rodgers & Abraham 1995; Moen *et al.* 1996; Moen, Pastor & Cohen 1997; D'Eon *et al.* 2002), which are recorded for each location in GPS radio-collar data. However, unequivocal quantitative methods of screening GPS radio-telemetry data are currently unavailable.

In this study we tested the effects of position (angle from vertical) and orientation (compass direction) on GPS radio-collar fix rates and horizontal (i.e. x–y coordinate grid) location errors, to provide quantitative information on potential bias and error associated with animal activity in radio-telemetry research. We also investigated the use of positional dilution of precision as a means of data screening to reduce horizontal location error in applied work.

Materials and methods

We tested the effects of radio-collar position and orientation on radio-collar performance using five stationary GPS radio-collars (Advanced Telemetry Systems, Isanti, MN) in an open, grassy field (0% canopy closure) in south-east British Columbia, Canada (49°27′N, 117°34′W), between 18 June and 19 July 2003. The collars were placed simultaneously in five positions: 0° (radio-collar vertical with GPS antenna facing directly at the sky), then 45°, 90°, 135° and 180° from vertical (180° = GPS antenna facing directly at the ground). Collars were also rotated in each of the four cardinal directions (north, south, east, west) in each position, except 0° and 180° where no aspect applied. Collars were 50 cm from the ground. Collars (= replicates) were set to attempt GPS fixes every 15 min, and ran for 24 h in each position and orientation combination (= treatments), providing five replicates of 14 treatments.

We calculated fix rates for each replicate (collar) and treatment as the proportion of total possible GPS locations obtained by radio-collars in a 24-h period (i.e. 100% = 96 locations). We calculated the horizontal location error for each location recorded by the radio-collars by calculating the mean horizontal error of each location, then calculating a mean error for each replicate (collar) and treatment. Horizontal error was calculated as the linear distance between the recorded location (collar data) and an assumed true location measured with a Leica Geosystems GS20 GPS unit (Leica Geosystems AG, Heerbrugg, Switzerland), which provided submeter accuracy using post-processing differential correction (MELP 2001). Radio-collar data were not corrected because we were primarily concerned with relative treatment effects, and we wished to investigate the accuracy of uncorrected data.

Treatment effects were tested using one-way (to test treatment effects individually) and two-way (to test interaction effects) analysis of variance designs (Zar 1984). In this way, tests of statistical significance were performed using radio-collars as the experimental unit, not individual locations, as recommended by Alldredge & Ratti (1986) and Aebischer, Robertson & Kenward (1993).

We used positional dilution of precision (PDOP) to investigate the relationship with location error using individual locations. PDOP is a 3-D measure of the quality of GPS data where lower values usually indicate higher location accuracy. Individual locations would be the relevant unit when screening data in applied work. We systematically screened data by removing locations with PDOP values higher than a given limit, and calculated location error parameters of resultant data. We used PDOP limits of three, four, six, eight, and 10 based on recommendations provided by MELP (2001) for GPS survey accuracy. We also investigated the option of removing 2-D fixes because 2-D fixes are less accurate than 3-D fixes and therefore provide a similar kind of option to researchers for data screening. To investigate the trade-off between data loss and location accuracy, we concurrently calculated the amount of data that would be lost in each procedure.

Results

Among orientation classes, fix rates were highest for south (mean = 98·7%, SE = 0·74), followed by east (mean = 96·9%, SE = 1·55), west (mean = 94·0%, SE = 2·72) and north (mean = 93·6%, SE = 3·78), but differences were not statistically significant ($F_{3,56}$ = 0·964, P = 0·416; Fig. 1). Location error was lowest for south (mean = 8·2 m, SE = 0·91), followed by east (mean = 10·7 m, SE = 1·32), west (mean = 10·9 m, SE = 1·58) and north (mean = 12·2 m, SE = 1·72), but differences were not statistically significant ($F_{3,56}$ = 1·390, P = 0·255; Fig. 1).

Among position classes, fix rates were highest for 0° (mean = 100·0%, SE = 0·00) and 45° (mean = 100·0%, SE = 0·00), followed by 90° (mean = 99·4%, SE = 0·29), 135° (mean = 87·8%, SE = 3·07) and 180° (mean = 76·0%, SE = 7·80), and differences were statistically significant ($F_{4,65}$ = 13·028, P < 0·001; Fig. 2). Location errors were lowest for 0° (mean = 3·4 m, SE = 0·28), followed by 45° (mean = 5·6 m, SE = 0·201), 90° (mean = 9·5 m, SE = 0·57), 135° (mean = 16·4 m, SE = 1·13) and 180° (mean = 17·0 m, SE = 1·72), and differences were statistically significant ($F_{4,65}$ = 39·361, P < 0·001; Fig. 2).

No significant interactions between orientation and position occurred for fix rates ($F_{6,48}$ = 1·508, P = 0·196) or location errors ($F_{6,48}$ = 1·228, P < 0·309). A general, but weak, trend towards higher location errors occurred as a function of higher PDOP values when individual locations (n = 6359) were plotted against individual PDOP values (R^2 = 0·256; Fig. 3). Using all data, mean location error was 10·5 m (SE = 0·22), with 95% and 100% circular error probable values of 28·9 m and 587·5 m, respectively (Table 1). Locations errors were reduced to a mean of 7·3 m (SE = 0·13), with 95% and 100% circular error probable values of 19·4 m and 149·3 m, respectively, but resulted in 37·5% of data discarded when only locations with PDOP values < 3 were used (Table 1).

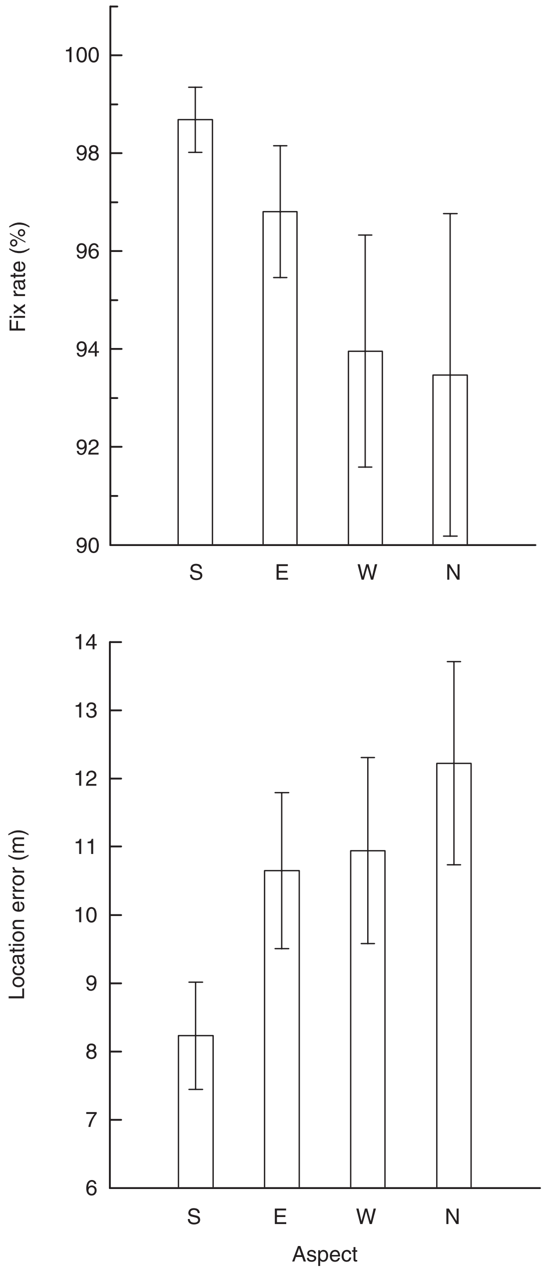

Fig. 1. Mean (± SE) fix rates and location errors among orientation classes [south (S), east (E), west (W), north (N)] for five stationary GPS collars in south-eastern British Columbia, Canada, June–July 2003.

Discussion

Despite a consistent trend towards slightly better performance when collars were facing south, orientation had no statistical effect on fix rate or location error. This is consistent with D'Eon *et al*. (2002), who found similar effects, and suggests that researchers can safely assume orientation alone will not impose large biases into GPS radio-telemetry data. A caveat of this result is that our study was performed in relatively flat, open terrain. An important variable that may present confounding effects is the amount of available sky (for discussion of available sky see D'Eon *et al*. 2002), where a collar on an animal on a steep slope will have less available sky than one in a topographically flat and open area.

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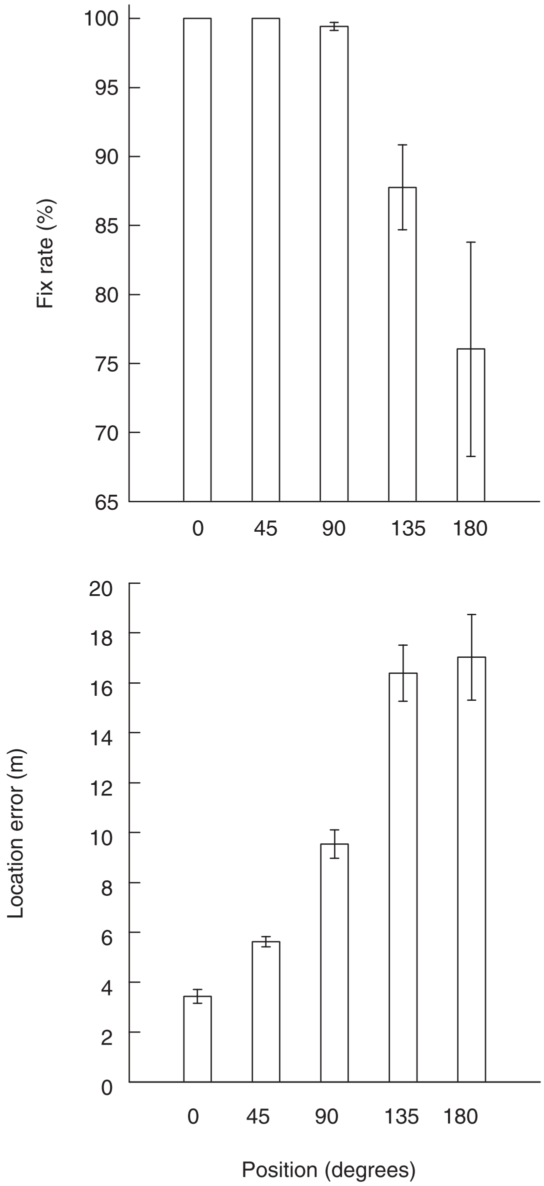

Fig. 2. Mean (± SE) fix rates and location errors among position classes (degrees from vertical) for five stationary GPS collars in south-eastern British Columbia, Canada, June–July 2003.

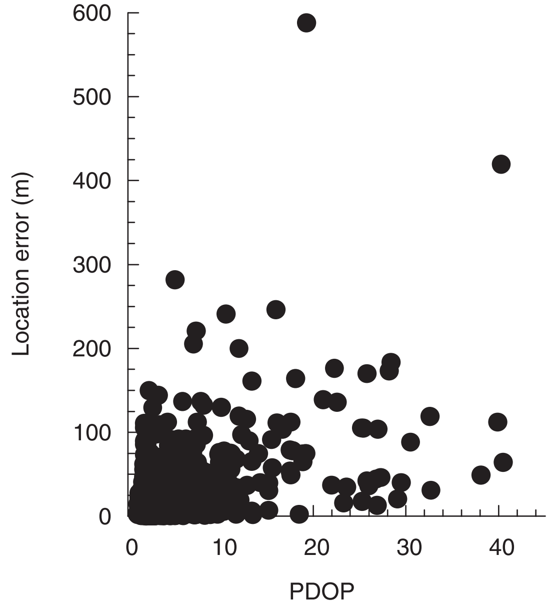

Fig. 3. PDOP vs. location error for 6359 locations from five stationary radio-collars in south-eastern British Columbia, Canada, June–July 2003.

The largest source of variation in fix rate and location error in this study was radio-collar position. We found a consistent downward trend in both parameters as collars angled away from vertical. However, there was little difference in performance between 0° and 90°, with larger negative impacts on performance occurring in the 135° and 180° positions, suggesting a threshold effect at 90°. This has important implications for researchers, who should ensure radio-collars are deployed such that they remain vertical on the animal. It also implies that collars that are known to be off-vertical (e.g. an animal is spotted after deployment) are still viable provided the collar is between 0° and 90°. Further, despite lower performance in the 135° and 180° position, the fact that we obtained 75% of locations on average in these positions (albeit with higher

Table 1. GPS radio-collar location error mean, median and frequency percentiles for a variety of data screening options from five stationary GPS radio-collars in south-east British Columbia, Canada

Criterion*	Data reduction† (%)	Location error (m) Mean (SE)	50%‡	95%‡	99%‡	100%‡
All data	0·0	10·5 (0·22)	5·9	28·9	74·7	587·5
PDOP < 3	37·5	7·3 (0·13)	5·1	19·4	34·8	149·3
PDOP < 4	17·4	7·7 (0·12)	5·4	20·8	39·2	149·3
PDOP < 6	4·2	8·5 (0·13)	5·7	23·7	46·4	281·3
PDOP < 8	2·2	8·9 (0·15)	5·8	25·1	52·5	281·3
PDOP < 10	1·3	9·1 (0·15)	5·8	26·2	54·8	281·3
3-D only	7·7	8·8 (0·16)	5·7	24·1	53·6	281·3

*Criterion used to screen data. PDOP, positional dilution of precision; 3-D only, 3-D fixes only.
†Proportion of data removed from the analysis based on the criterion. All data $n = 6359$ locations.
‡Also referred to as 50%, 95%, 99%, and 100% CEP (circular error probable), where the value in m indicates the radius of a circle (with the true location at its centre) within which the specified proportion of locations occur. For example, for all data, a circle with radius 5·9 m and centred around the true location, will contain 50% of recorded locations.

location error) implies that useful data can be obtained from a collar that comes to rest in the 180° position on a study animal. We attribute successful locations in this position to reflected signals off the ground, which will vary with substrate conditions (MELP 2001). Therefore, results from a collar in the 180° position are likely to vary with conditions.

Our results also imply that the link between animal activity and collar positioning should be an important factor in the issue of error and bias in GPS radio-telemetry, because animal activity should greatly influence collar positioning relative to the sky. As our results show reduced performance with lower collar angles relative to the sky or horizon, animal activities that place collar antennae at low angles (e.g. foraging, bedding, digging) will have higher bias than other activities that place collar antennae at higher angles (e.g. walking). This could lead to errors in research conclusions. Our findings are consistent with Bowman *et al*. (2000), who reported lower fix rates among bedded deer *Odocoileus virginianus*, and Moen *et al*. (1996), who reported lower fix rates among moose when collar position was horizontal. More work of this nature, specifically to quantify the link between specific animal movement and resulting bias in GPS radio-telemetry data, is required so that definitive and quantitative research recommendations can be made.

PDOP can be used as a means to screen GPS radio-telemetry data and reduce location error by deleting locations thought to be highly inaccurate (Rempel, Rodgers & Abraham 1995; Moen *et al*. 1996; Moen, Pastor & Cohen 1997; D'Eon *et al*. 2002). However, inconsistencies have been reported in the general trend between high PDOP and high error. Researchers in these cases have therefore been reluctant to recommend strict rules for data screening. Indeed, there were cases in this study where PDOP was high and location error was low, and vice versa (e.g. in our data, three locations where PDOP was > 10 had location errors < 10 m; Fig. 3). This inconsistency makes the establishment of a rigorous PDOP-based screening method difficult. None the less, a general trend among studies appears consistent where high PDOP values reflect high location errors. In our data, 79 locations with PDOP > 10 had a mean location error of 82·6 m (SE = 10·09), which is an order of magnitude higher than the mean errors of other data sets in Table 1. The primary effect (advantage) of omitting locations over a specified PDOP in our analyses was deleting outliers. For example, using a PDOP limit of 10 did not significantly change the average location error from uncensored data but effectively brought the 95% and 100% CEP (circular error probable). down from 74·7 m and 587·5 m, to 54·8 m and 281·3 m, respectively (Table 1).

The largest concern associated with omitting locations for any reason is the potential for systematically introducing additional bias into the data. Thus, the situation becomes a trade-off between increasing location accuracy of the data and the possibility of introducing new biases. From our analyses, using a PDOP limit of 3 considerably increased location accuracy but resulted in the omission of 37·5% of all locations (Table 1). Most would agree that this is an unacceptable level of data removal and does not justify the increase in location accuracy. However, using a PDOP limit of 10 effectively removed major outliers from the data with only a 1·3% data reduction, perhaps offering a practical alternative. Deleting 2-D locations had similar effects on accuracy but resulted in 7·7% data reduction, a questionable amount of data reduction. Clearly, more work is required to quantify the effects of data removal on GPS radio-telemetry data analyses and to provide more clarity regarding the issue of this trade-off.

APPLICATIONS AND RECOMMENDATIONS

GPS radio-telemetry is likely to increase in popularity and become a standard wildlife research technique. However, the current challenges surrounding issues of error and bias in GPS radio-telemetry data require further refinement. Based on the results from this study, we make the following recommendations to researchers and managers engaging in GPS radio-telemetry.

In this study orientation (aspect) did not statistically affect GPS radio-collar performance and can therefore be safely disregarded as a potential source of error and bias. However, this conclusion is based on our work in western Canada, and may or may not be the case in other parts of the world. Studies such as ours should be repeated elsewhere (e.g. southern hemisphere) to validate our results on a global scale. As it is the orbital paths of GPS satellites relative to locations on Earth that provide variability in satellite availability, and therefore satellite acquisitions rates and fix-rate success, different results may occur in other areas of the world.

Collar position appears to be extremely important and care should be taken to ensure collars remain between vertical and 90° on study animals. In addition, the link between animal activity, collar position and error and bias in ensuing data must be quantified to understand fully the influence of animal activity on GPS radio-telemetry data. As activity varies among species, individuals and during different times of the day and year, bias and error in resultant data will be a function of these factors and most probably unique to individual species and activities. If a radio-collared animal that digs while foraging or for other reasons keeps its head at low angles or beneath solid objects for prolonged periods, this activity could potentially translate into significantly lower fix rates than at other times, and would result in proportionally fewer recorded locations for this habitat type. This could lead to the research conclusion that these locations are used infrequently or even avoided, when in fact the opposite is true. If these kinds of consistent biases can be established, the associated errors and bias could be corrected.

The use of PDOP as a data screening technique has potential applications in applied work, but researchers

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must consider the trade-off between increased accuracy and potentially introducing new biases. In our case, a PDOP limit of 10 substantially increased accuracy by deleting outliers, with an arguably acceptable amount of data reduction. We recommend against screening data on the basis of 2-D locations as it can result in a relatively high amount of data reduction.

Finally, this study was performed in relatively flat and open terrain. We chose these conditions because it was the first study of its kind in the published literature, and represented a suitable starting point for investigating issues concerning GPS radio-collar position and orientation. However, future work should incorporate multiple habitat types and should test the effects of vegetation type, canopy closure, terrain and other habitat factors that have been demonstrated to effect GPS radio-telemetry results (Dussault *et al*. 1999; D'Eon *et al*. 2002; Frair *et al*. 2004). This would increase the applicability of results to researchers and practitioners in the field experiencing the complexities of multiple habitat types.

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