Addendum – Detailed Methodology

Observation data

We used snow tracking data to construct encounter histories to fit to the occupancy model. Observers drove roads during the wintertime, and recorded locations of wolf tracks, and the number of wolf tracks that were observed. Survey routes were recorded either from GPS track-lines or were digitized post hoc from a combination of traced maps and verbal descriptions of surveys. Survey effort was allocated based on survey blocks conveniently delineated by roads and natural features such as rivers. Analysis sample units were 100 hexagonal cells placed over the union of all tracking blocks in the wolf core range (or domain of inference - see below), which was the optimal size identified by a simulation analysis (Stauffer et al. 2021). We accounted for survey effort using the length of geo-referenced tracking routes surveyed in each grid cell. Repeat surveys in tracking blocks usually were ≥ 7 days apart. Therefore, we defined survey occasions as 7-day periods over the duration of the tracking season. The first survey was conducted on 23 November 2021 and the final survey on 01 April 2022, resulting in 19 survey occasions. In total, survey effort was more than 27,000 km, compared to 19,900 km the previous year (because of the Feb 2021 hunt, only 14,000 km of pre-hunt survey effort were considered in the model). For each occasion, we collapsed all detection data within cells to detection/non-detection data, and if multiple surveys were conducted in a cell within one 7-day period, we also likewise collapsed those data.

Defining core wolf range

The scaled occupancy approach is intended to provide an abundance estimate for pack- associated wolves, and consequently it is important to delineate the domain of inference (or core range) to which the estimate applies, and to avoid predicting wolf occupancy into areas where there may be transient wolf presence but no evidence of pack activity. DNR uses data from previous tracking seasons and other confirmed reports of pack activity to define core wolf range. The 2021–2022 core range is shown in Figure 3, and this area represents the area of inference for the population estimate produced from the 2021–2022 tracking data. While there may be additional wolves outside the core range, and evidence of such wolves may influence management recommendations from the wolf advisory committees, those wolves are not included in the core range model estimate.

The core range is defined based on data prior to the current tracking season, and further adjustments are implemented in the following year. For example, if a wolf pack is observed outside of the core range during the 2021–2022 tracking season, then that tracking block will be added to the core range for the 2022–2023 tracking season. The total area of the core range in 2022 was 74,663 km^2, comprising 156 tracking blocks (there were additional surveys in one block outside the core area), as compared to 73,797 km^2 in 2021, comprising 154 tracking blocks.

The criteria for inclusion in core wolf range based on tracking data during the previous 4 seasons. Four years was identified as the number of years which allowed the core range to respond to possible expansions and contractions of wolf range, while minimizing inclusion or exclusion based on transient wolf movements or imperfect detection of wolves in pack- occupied areas. The criteria for inclusion are as follows (with any criteria being met resulting in inclusion):

- Tracks from at least two wolves were observed within a block during a single tracking event
- Single wolf tracks were observed in a grid during separate surveys within a tracking season

Beyond track observations, only confirmed evidence of pack activity in a block will trigger its addition to the core wolf range. Requiring evidence of pack activity reduces the potential for positive bias that may result from adding blocks based on observations of lone wolves whose occupancy within a grid cell is often transitory. Evidence of pack activity is defined as any of the following:

- Confirmed depredation events that included multiple wolves
- A photo with multiple wolves
- Multiple photos of single wolves reported within a block and year

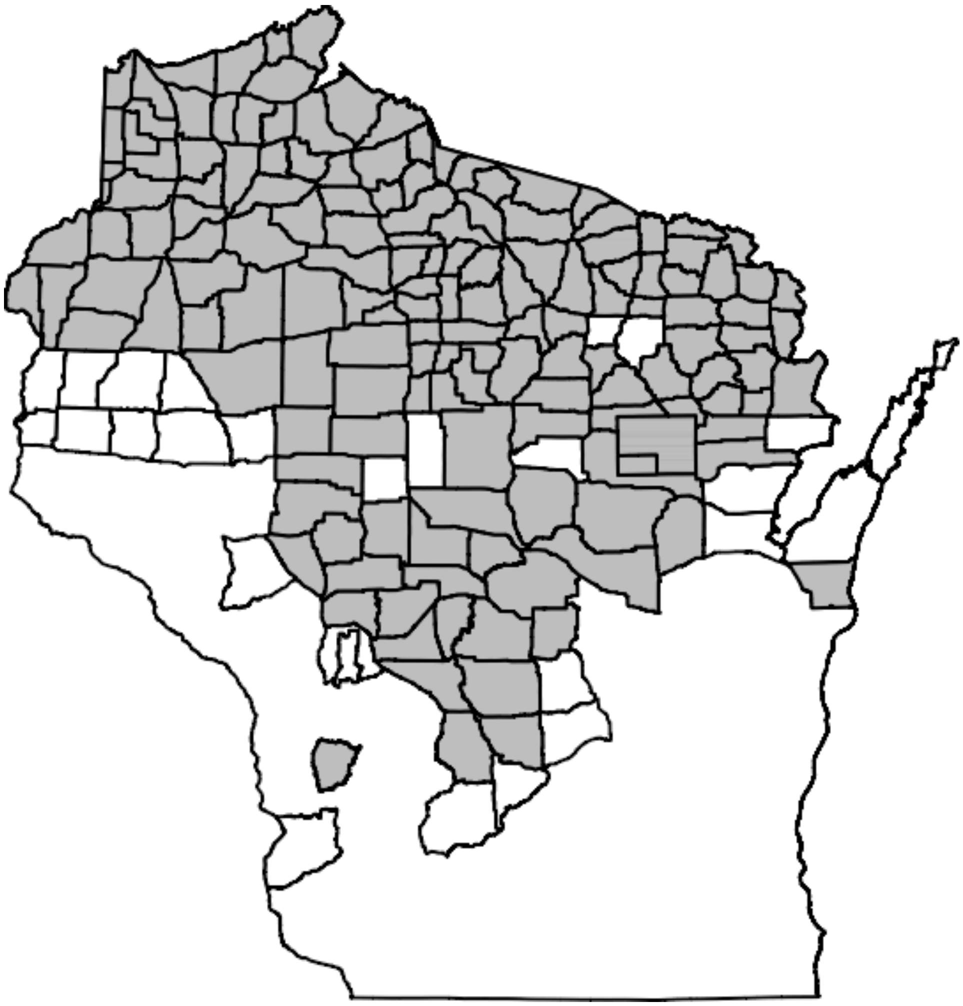

Figure 13. Core wolf range for winter 2021–2022, with tracking blocks included (gray) and excluded (white).

The occupancy model

We used a Bayesian modeling approach which provides flexibility for developing models, facilitates easy propagation forward into the posterior distribution of all the uncertainty contained in the various model inputs, and produces a posterior estimate for straight-forward interpretation. We fitted our data to the model, using the tools found in the R package NIMBLE. The model had the following structure:

$$z_i \sim Bernoulli(\psi_i)$$
$$logit(\psi_i) = b_0 + b_1 \times forest_i + b_2 \times ag_i + b_3 \times road\_density_i$$
$$y_{it} \sim Bernoulli(z_i p_{it})$$
$$logit(p_{it}) = \beta_0 + log(effort_{it})$$

where ψ_i is as described above; ag_i and $forest_i$ are the proportion of agriculture and developed land, and forest cover, respectively, in sample grid i, as calculated from the 2016 NLCD data; and $road\_density$ is the density of primary, secondary, and forest roads in sample grid i, in km/km^2. All covariates for ψ were scaled and centered to facilitate better model convergence. In the detection model, p_{it} is the probability that any wolf tracks are detected in grid cell i during survey t, and $effort_{it}$ is the number of kilometers traversed in grid cell i during survey t.

Mean pack size

We calculated zone-specific pack size using the following approach:

1. Divide the area into hexagonal grids, as described above, but of a size matching mean home-range size (171 km^2).
2. Eliminate any observation where tracks indicate only a single wolf.
3. Eliminate any cells where tracks (or tracks of size > 1) were not observed.
4. For the remaining cells, determine the largest enumerated set of tracks in each cell.
5. Calculate statistics.

We used this method to calculate zone-specific mean pack sizes using the 2021–2022 tracking data.

Mean home range size

Mean home range size was estimated from GPS locations from 01 Dec 2020 — 21 Feb 2021 and 01 December 2021 -– 15 April 2022 for 23 and 18 collared wolves, respectively. Our goal was to estimate the size of the area reasonably appropriated by each pack, rather than to strictly estimate the actual area used by each pack. Maximum convex polygons (MCPs) often underestimate home range size and are very sensitive to the inclusion or exclusion of potential outliers. Kernel density estimators (KDEs), on the other hand, can result in fragmented or convoluted home ranges, depending on the choice of a smoothing parameter h. Consequently, we used the following combination approach. We used the kernelUD function from the R package adehabitatHR to calculate kernel density estimates for each pack. For each pack we:

1. Calculated a standard reference smoothing parameter $href = \sigma \, x \, n^{-1/6}$, where $\sigma = 0.5(\sigma_x + \sigma_y)$ was the mean of the standard deviations of the x and y coordinates of the n GPS locations. This is the default h used by the kernelUD function.
2. Iteratively estimated the utilization distribution (UD) and computed the 95% KDE for a range of values $h = href \, p$, where p was incremented by 0.1 from 0.4 to 2.5.
3. Identified the first value of p that resulted in a 95% KDE polygon that was contiguous (this can be done automatically in an R script without visually inspecting the KDE polygon). In many cases, the home range at this point still had an inadvisably irregular shape.
4. Increased p by 0.2, and calculated the area of the resulting 95% KDE home range.
5. Compared the calculated area with the area of the corresponding MCP, and

considered max(95%KDE, MCP) to be the appropriate area co-opted by the pack. We considered that, if area(MCP) > area(95% KDE), then selecting the MCP was justified on the grounds that the MCP was likely including an area of the landscape excluded by a concave portion of the KDE home range, but probably also largely excluded from use by adjacent packs.

6. Individually examined exceptional cases where the KDE or MCP was implausibly large (> 400 km^2, or about 2.5X the previous year's mean HR size). For very large, over- smoothed KDEs, we instead used the smaller MCP as more reasonable representations of home ranges.

Using the above approach, we estimated a mean pack home range size of 171.45 km^2 ($SE = 15.17$). While zone-specific estimates of home range size are desirable, it is not currently feasible given insufficient samples sizes that would result in highly imprecise estimates, which would propagate considerable extra uncertainty into the abundance estimates. Therefore, we use the overall mean, rather than zone-specific values, for the abundance estimate. However, collaring effort is allocated among zones to produce home range estimates that are broadly representative of the core range.

Scaled occupancy estimate

Abundance was estimated as □=Σ□□□□□□□□/□, where □□ was the probability of occupancy in sample unit *i*, □□ was the area of sample unit *i*, □ is the mean two-year home range size, and □*i* is the cell-specific (zone-specific) mean pack size. The uncertainty captured in each of the intermediate estimates is propagated into the abundance estimates, resulting in a posterior distribution which we report as a posterior model (most likely value) and 95% credible intervals.