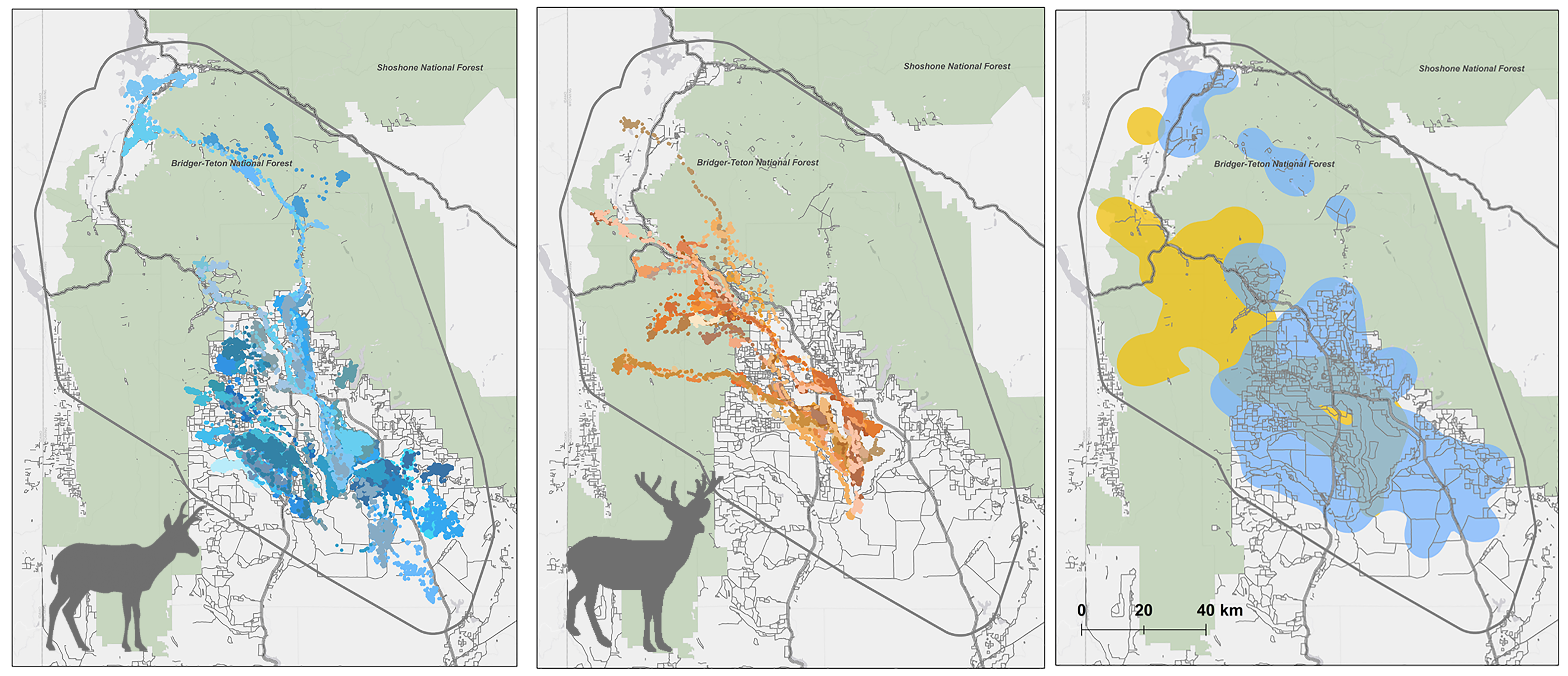
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# Barrier Behavior Analysis (BaBA) reveals extensive effects of fencing on wide-ranging ungulates: Supporting Information

## Figure S1. Movement tracks and home range of pronghorn and mule deer.

GPS data for the 24 pronghorn-years (left) and 24 mule deer-years (middle), and 95% kernel density home range (right) generated from the pronghorn (blue shade) and mule deer (yellow shade) GPS data.



## Appendix S1: BaBA step-by-step procedures and introduction to R package “BaBA”

BaBA (Barrier Behavior Analysis) is a function of the R package “BaBA” (available at [github.com/wx-ecology/BaBA](https://github.com/wx-ecology/BaBA/)) that classifies barrier encounter events into six categories: *quick cross*, *average movement*, *bounce*, *trace*, *back-and-forth*, and *trapped*. These categories describe spatial and temporal characteristics of movement segments near barriers and interpretations of their ecological consequences need to be situated in species and environmental contexts. Below, we first introduce the six parameters used in BaBA and describe how these parameters are applied to classify behaviors. Then, we use our pronghorn and mule deer case study to discuss how to assign values to the BaBA parameters. The workflow of the BaBA process is demonstrated in Figure S1.1 and an overview of major criteria for each behavior type is listed in Table S1.1. To install the latest development version of BaBA, in an R session, type:

*devtools::install\_github("wx-ecology/BaBA”)*

### BaBA parameters and process

* **d:** barrier buffer distance, in meters, if the barrier is in projected coordination system. Otherwise, in units of the barrier layer. The width of the barrier buffer will determine which GPS positions are considered in close proximity to barriers.
* **tb:** The maximum duration of an encounter event to be considered as a short barrier interaction (i.e. *quick cross* or *bounce*), in hours.
* **tp:**The minimum duration of an encounter event to be considered as a prolonged barrier interaction (i.e. *trapped*), in hours.
* **w:** window extent, in days. Defines the length of a time period where a moving window method will be applied to calculate average movement straightness.
* **tolerance:** Maximum duration to allow some occasional GPS locations to be outside of barrier buffer in one continuous encounter event (see caveats section below), in hours.
* **max\_cross**: Maximum number of crosses (trajectory-barrier intersections) allowed in *trace* and *back-and-forth* behavior (see caveats section below).

BaBA identifies and groups any continuous GPS positions that are within **d** of barriers as encounter events. Based on its duration **ti**, an encounter event is identified as short (**ti < tb**), median (**tb < ti < tp**), and prolonged (**ti > tp**). Any prolonged event with **ti** longer than **tp** is classified as *trapped*.

For short events, BaBA extends the event trajectory by including one movement location before and one after the encounter event. If the extended trajectory intersects a fence line, the event is classified as *quick cross*. If the extended trajectory has no intersection with any fence line, it means the animal stayed for a short amount of time within the fence buffer area and quickly moved away: the event is labeled as *bounce*. When the location before and/or after the event trajectory is missing (such as when the encounter event is at the beginning or the end of the GPS record) and no crossing of a barrier is identified with the locations available, the event is labeled as *unknown*.

For median events, BaBA calculates movement segment straightness (**stri**) of each event to evaluate whether the focal event is different from average movementstraightness. Straightness is a telling indicator of barrier effects because linear barriers like fencing and roads often alter movement path orientation and animals cannot keep heading straight along their original movement direction unless they are parallel to the barrier. Path straightness is the ratio between the displacement distance and the accumulated step length of a trajectory, ranging from 0 (sinuous) to 1 (straight) (Benhamou, 2004). Because baseline movement straightness can vary greatly across individuals and time, especially for migratory animals, we calculate local average straightness () and standard deviation () by applying a moving window method on all **ti**-hour movement segment (same duration as the focal event) from **w/2** days before till **w/2** days after the focal event. The window moves along the movement trajectory within the defined time period one location at a time. Given certain GPS interval **int**, the total number of sampled movement segments is **w\*24/int+1**. For example, to calculate a 7-day baseline straightness for an encounter event that lasts 10 hours and with a 2-hour GPS interval, BaBA calculates the average () and standard deviation () straightness of all 10-hour movement segments starting at or after 3.5 days before the encounter event and ending at or before 3.5 days after it (85 segments in total). The user may choose to exclude any location that falls within a barrier buffer using “**exclude\_buffer**” argument in the function and the straightness will only be calculated on **ti**-hour-long segments that are constituted of continuous locations outside of barrier buffers. When the barrier deployment is dense, however, choosing to do so can greatly reduce the number of straightness measurements that are averaged over. Therefore, in our pronghorn and mule deer case study, we included all GPS locations to calculate the average straightness ().

With and calculated, BaBA uses one-standard-deviation criteria to determine whether the target encounter event is different from the average movement at the time. Encounter events are classified as an *average movement* if **stri** is within , *back-and-forth* if **stri**  < (the movement of the encounter event is more sinuous than the normal), and *trace* if **stri** >  (the movement of the encounter event is less sinuous than the normal). When there is less than half of **w\*24/int+1** movement segments included in the calculation of and , the encounter event will be classified as *unknown*.

### Caveats of BaBA

Misclassifications can occur in BaBA and here we listed some of the common causes and potential solutions.

1. **Curvy, zig-zagged, or discontinuous barriers with the inadequacy of GPS trajectory in representing actual movement routes (often related to coarse GPS temporal resolution).** When barriers are curvy or discontinuous, GPS trajectories between two locations can result in some intersections with the barriers even though the animal did not cross the barrier. This is especially problematic for *back-and-forth* and *trace* events because these behaviors are assumed to happen along one relatively straight fence line. To counter this problem, BaBA has an adjustment parameter **max\_cross** to allow some trajectory-barrier intersections in *back-and-forth* and *trace*. When intersections are greater than **max\_cross**, the event will is reclassified as *unknown*.
2. **High GPS temporal resolutions. This is an opposite problem as listed in (1).** Theoretically, high-frequency GPS data can capture nuanced animal movement near barriers (e.g. Bischof et al. 2019), and applying BaBA on such data may achieve higher classification accuracy. However, when more details of movement are captured, a clear-cut setting of barrier buffer distance across the whole landscape may exclude many median-long encounter events when animals just shortly go farther away from barriers but quickly come back. Even though it is not a specific problem we encounter in our case study, users can specify a **tolerance** in the BaBA function of our R package to tolerate some occasional GPS locations outside of barrier buffer in one continuous encounter event.
3. **High barrier density and messy barrier deployment.** Using our case study as an example, fences are denser around towns, causing some identified barrier encounter events actually composed of several continuous encounter events spread across multiple fence buffers, and many of these events are classified as *trapped*. If using data with higher GPS temporal intervals, such events might be broken down into a couple of ***normal***and ***altered*** events. Such cases are not necessarily false classification, but nuanced behavioral responses might be overwhelmed by the prolonged length of the encounter event. One solution is to have very well IDed barrier layers so one can count for the number of different barrier buffers one encounter event crosses (not currently implemented in BaBA).

### Parameterizing BaBA: pronghorn and mule deer case study as an example

Determining fence buffer distance **d** is critical. When **d** is too small, crossing events may be missed. When **d**is too large, extra locations will be included and events might be misclassified. Because we lack empirical knowledge of the distance at which pronghorn and mule deer react to fences, we used *quick cross* events to identify the optimal fence buffer distance for each species of interest. As **d** increases and more movement points get included in the buffer area, *quick cross* events will first increase then fluctuate or decrease (Figure S1.2). Alternatively, users may use resource selection function to quantify animals’ response to fences (e.g. Stabach et al. 2016) and use the response curve as guidance for determining **d**. By applying fence buffer distances every 10 meters from 50m - 150m, we define the optimal buffer as the distance at which the number of *quick cross* events begins to level off (< 1 % increase). We defined **tb** and **tp** as 4 hours and 36 hours, respectively, based on local biologist recommendations. We used 7 (168 hours) for **w**. We recommend users balance target species ecology (e.g. movement rate and scale), barrier density, research or management objectives, and data quality (e.g. temporal intervals and spatial accuracy) when determining **tb**, **tp**, and **w**. To most accurately classify *back-and-forth* and *trace* behaviors near discontinuous or irregular fences, we visualized 10% of randomly selected median encounter events and decided to set **max\_cross** as 4. We reclassified such behaviors with >4 intersections with fences as *unknown***.**

### References

Benhamou, S. (2004). How to reliably estimate the tortuosity of an animal’s path: Straightness, sinuosity, or fractal dimension? *Journal of Theoretical Biology*, *229*(2), 209–220. https://doi.org/10.1016/j.jtbi.2004.03.016

Bischof, R., Gjevestad, J. G. O., Ordiz, A., Eldegard, K., & Milleret, C. (2019). High frequency GPS bursts and path-level analysis reveal linear feature tracking by red foxes. *Scientific Reports*, *9*(1), 8849. https://doi.org/10.1038/s41598-019-45150-x

Stabach, J. A., Wittemyer, G., Boone, R. B., Reid, R. S., & Worden, J. S. (2016). Variation in habitat selection by white-bearded wildebeest across different degrees of human disturbance. *Ecosphere*, *7*(8), 1–17. https://doi.org/10.1002/ecs2.1428

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### **Figure S1.1: BaBA workflow.**

The two dataset required by BaBA are animal movement data that includes individual ID, GPS coordinates, and date (a SpatialPointsDataFrame) and barrier locations (a SpatialLinesDataFrame). BaBA first identifies barrier encounter events composed continuous animal locations fall in barrier buffers. *Tolerance* allows certain amount of animal locations outside of the buffer to be included in one encounter event. These encounter events are subsequently classified into one of the six barrier behaviors based on duration and movement trajectory straightness.

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### ***Figure S1.2: Number of quick crossing events identified as fence buffer distance increases.***

When the buffer is too small, crossing events may not be sufficiently included in the buffer. When the buffer is too large, extra locations will be included in the buffer. In this case, the events might be classified as back-and-forth or normal movement because of lasting trajectory duration.

### Table S1.1 Overview of major criteria for each barrier behavior type

|  |  |
| --- | --- |
| Behavior Category | Criteria |
| Quick cross | t < tb; barrier intersections = 0; |
| Average Movement | tb < t < tp; - σ < str < + σ; |
| Bounce | t < tb; barrier intersections 0; |
| Back-and-forth | tb < t < tp; str < - σ; barrier intersections < max\_cross; |
| Trace | tb < t < tp; str > + σ; barrier intersections < max\_cross; |
| Trapped | t > tp; |

# Appendix S2: Sensitivity Analysis

To test the sensitivity of BaBA results to the parameter setting and data quality, we adjusted the below parameters and compared the results of the new scenarios to the original settings for both species (Supp 3 Table 1). P0 and M0 stand for the original parameter settings for pronghorn and mule deer, respectively. Note that we did not adjust **tb** because calling a prolonged barrier movement *quick cross* or *bounce* might not be ecologically meaningful for pronghorn and mule deer.

* P1/M1, adjust *average movement* one-standard-deviation criteria to half-standard-deviation. Namely, for median encounter events, when the straightness **stri** is within , the event will be classified as an *average movement*.
* P2/M2, adjust **tp**, from 36 hours to 18 hours (-50%). We did not test for +50% because that will eliminate almost all *trace* events;
* P3/M3 and P4/M4, adjust **w** from 7 days to 10.5 days (+50%) and 3.5 days (-50%).
* P5/M5, resample GPS locations from 2-hour interval to 4-hour interval.

The sensitivity analysis results (Table S2.1) showed that the change of classification parameters do not affect the general conclusion we draw from the results. As expected, P1/M1 showed that the *average movement* rule affects the relative proportion of the three behavioral types of median encounter events: *average movement, trace,* and *back-and-forth*. Notably, *back-and-forth* maintained to be more frequent than *trace* for both species, even though an increase in *trace* proportionally was relatively more significant*.* The purpose of this parameter is to allow users to restrict or to relax their standards on “what is considered as a *normal movement*”.

Because classification of the *trapped* events solely depends on **tp**, P2/M2 had significant impacts on the detection rate of *trapped* events but on other events for both species. Users should determine this parameter based on the question “how long is too long for one animal stays near barriers”. P3/M3 and P4/M4 showed that **w** only slightly affected behavioral classification results, confirming the robustness of our classification procedure for median encounter events.

BaBA based on 4-hour GPS temporal interval did not change the relative proportions among different barrier behaviors compared to results based on the original 2-hour data (Figure S2.1, P5/M5). As expected, optimal fence buffer distance increased for both species because fewer encounter events can be detected within original fence buffer areas, including *quick cross* events that are used to determine optimal fence buffer distance. The total encounter event decreased more for pronghorn than for mule deer (-33.1% vs. -23.5%). As a result, seasonal variations captured for both species also decreased (Figure S2.2). P5 and M5 results suggested that BaBA can work with relatively low temporal resolution data, yet it performs better with higher resolution data.

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### Figure S2.1: Annual individual frequency of barrier behaviors based on 2-hour and 4-hour GPS intervals.

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### Figure S2.2: Seasonal variability of barrier behavior based on 2-hour and 4-hour GPS intervals.

### Table S2.1: Sensitivity analysis parameter settings and results.

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