

Pairing automated mark-recapture and social network models to
explore the effects of landscape configuration on hummingbird
foraging patterns: Appendix S1

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Contents

PIT tag implantation procedure	2
Inserting the needle and implanting the PIT tag	3
Preparing the plunger	4
Attaching the plunger and inserting the tag	5
Closing the needle hole	7
List of materials	8
RFID recording station	10
Sender-Receiver model description	10
Background	10
Model description	11
Priors	12
Supplementary analyses	13
Summaries of feeder use	13
Movements following competitive interactions	14
Data summaries of birds that did not move	14
References	15

¹ PIT tag implantation procedure

² These instructions are written for a right-handed person doing the implanting. The implant procedure is best
³ performed last after all of the other tasks are completed (i.e., banding and measurements). The hummingbird
⁴ can be given a small amount of sugar water before the procedure, but if the bird is doing fine, it is best to
⁵ wait until after the implant procedure so the enlarged crop does not interfere.

⁶ The specialized equipment for the PIT tag implantation includes a foam pad (or another soft surface)
⁷ to place the hummingbird on (Figure S2). This procedure requires two people, one person to hold the
⁸ hummingbird and one person to implant the PIT tag. The person holding the hummingbird on the foam
⁹ pad will hold the body gently but firmly between their thumb and pointer finger so that the bird cannot
¹⁰ wiggle or escape. With their other hand they will gently hold down the tail. The holder can also use their
¹¹ pointer finger on the hand that is holding down the tail to gently lift up the feathers on the upper back to
¹² expose the bare skin where the lidocaine solution will be applied (Figure S3).



Figure S1: Customized banding station setup.

¹³ Using a clean cotton applicator, the lidocaine gel ([Akorn lidocaine hydrochloride jelly USP 2%](#)) is applied
¹⁴ to the exposed skin on the upper back of the hummingbird (Figure S4) and left to sit for a minimum of two
¹⁵ minutes for the numbing to take effect (Figure S5). While waiting for the lidocaine gel to take effect, the
¹⁶ PIT tag is placed in 70% ethyl alcohol to clean and disinfect the surface before implantation (the cap of the
¹⁷ bottle of alcohol works well for this, see Figure S2). The needle should be placed upright (a hole or split in
¹⁸ the foam works well for this, see Figure S2) so that the tag can be dropped into the needle and that it is easy
¹⁹ to pick it up for inserting. Next, place the clean PIT tag using the cleaned and disinfected forceps (clean
²⁰ them by placing them into the open bottle of alcohol, see Figure S2) into the needle. In order to facilitate



Figure S2: Set-up and hummingbird hold. The bird in the photograph is a green hermit hummingbird (*Phaethornis guy*) in Costa Rica.

21 the action of picking up the needle to place it onto the plunger (it needs to be screwed in to the plunger),
22 make sure to unclip/loosen the cap of the needle, but leave the needle in the cap to keep it clean for when
23 it is needed.

24 Next, expose the skin on the back of the hummingbird (Figure S3). There is a spot on the middle/upper
25 back that is naturally feather-free making it unnecessary to pluck any feathers. This can be done by either
26 the person who is doing the implanting or the hummingbird holder. In Figure S3, the holder is gently lifting
27 away the feathers on the back which then makes it easy for the implanter to access that area. The implanter
28 will then apply the lidocaine gel to the bare skin using a clean/new cotton applicator (Figure S4). After a
29 generous amount of the lidocaine gel is applied, you need to wait a minimum of 2 minutes for the numbing
30 to take effect (Figure S5). While you are waiting for the skin to numb, you can do other tasks such as clean
31 and disinfect the plunger, clean the tag and drop it into the needle, and make sure the cap is loosened but
32 not removed (see the details on those procedures below). Once the lidocaine has numbed the skin where the
33 needle will be inserted, apply a betadine antiseptic solution ([povidone-iodine, 10%](#)) with a new/clean cotton
34 applicator to disinfect the area before implanting the tag (Figure S6).

35 Inserting the needle and implanting the PIT tag

36 For the entire implant procedure, it will be very important for the person holding the bird to position
37 their hand in a way that makes room for the implanter. This can be accomplished by the holder lifting
38 up/holding away the area of their hand between their thumb and pointer finger (it can feel awkward while
39 still maintaining a secure hold on the hummingbird with those two fingers). Before starting the implant



Figure S3: Exposing the bare spot on the back of the bird. The bird in the photograph is a green hermit hummingbird (*Phaethornis guy*) in Costa Rica.

40 procedure, make sure the needle is separate/uncapped from its cover (but still sitting in it) and has the
41 clean tag in it. Then with the clean forceps in your left hand, gently lift up the skin, pick up the needle
42 from the base with your right hand, and then insert the needle (**the bevel facing up**) just under where
43 the forceps are lifting up the skin (Figure S7). When inserting the needle, take care to not nick/puncture
44 the underlying muscle, just the skin, which makes holding up the skin with the forceps extremely important
45 in this step. The needle should be inserted through the skin until the bevel is fully covered (Figure S8). If
46 the needle does not insert smoothly, making it difficult to get the bevel fully covered by the skin, you can
47 use the forceps to help push the skin by feeding it up the needle very gently.

48 It is important to note here that our procedure differed from previously published recommendations
49 (Bandivadekar et al. 2018). We held the needle on its own for this step due to the weight and imbalance of
50 the needle with the plunger attached. We felt that the risk of damaging the underlying muscle was greater
51 when using the needle with the plunger attached than when attaching the plunger at a later stage. However,
52 the needle must be held **very still** when attaching the plunger with the needle inserted (see below).

53 Preparing the plunger

54 It is important to make sure that the plunger is in a non-plunged position (i.e., ready to be plunged) *before*
55 inserting the needle into the hummingbird. Before placing it into that position, it must be thoroughly cleaned
56 by dipping it into the alcohol a couple of times and opening and closing the plunger. After cleaning, then
57 leave it in the non-plunged position, but make sure that the tip of the metal plunger is slightly inserted into
58 the track, otherwise it can move around and not plunge when you need it to.



Figure S4: Applying lidocaine gel to exposed skin.



Figure S5: With lidocaine gel applied, wait at least 2 minutes for the gel to take effect.

59 **Attaching the plunger and inserting the tag**

60 Attaching the plunger to the needle (**that is already inserted into the hummingbird**) is a very delicate
61 step and will require very steady hands and complete focus. The implanter will gently switch their hold of
62 the **inserted needle** from the right to the left hand while keeping it in place. Maintaining a steady and
63 gentle hold on the needle with the left hand, pick up the (clean and not-plunged) plunger and gently screw
64 it into the needle while holding the needle **very steady** so that it does not go in any further or come out
65 and expose the bevel (Figure S9). Make sure the plunger is fully screwed into the needle. Then slowly and
66 gently shift your grip on the plunger with your right hand in the position of pushing down the plunger.
67 While gently holding the needle in place with the forceps (Figure S10), slowly and steadily push the plunger

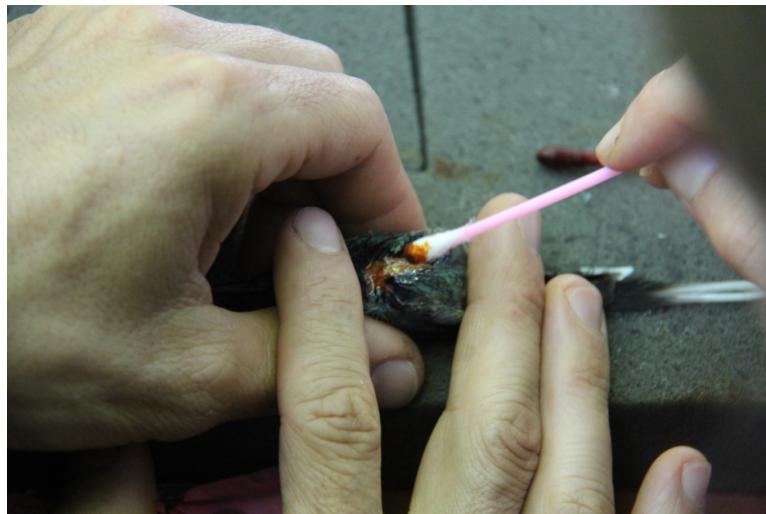


Figure S6: Cleaning the area with betadine antiseptic solution.



Figure S7: Inserting the needle, using forceps to lift the loose skin.

in. You will see the tag appear at the tip of the needle then continue inserting the plunger until the tag is fully expelled from the needle and under the hummingbird's skin. Once the tag is in the hummingbird and out of the needle, slowly remove the needle/plunger while continuing to gently hold the skin at the base of the entrance to keep the skin from being pulled (and tag expelled) when the needle is being removed. The tag should then be visible under the skin, and ideally you would have a little space between the needle hole and the inserted tag (Figure S11) which will make closing the hole easier.



Figure S8: Needle inserted under the skin.



Figure S9: Attaching the plunger by screwing it onto the needle while keeping the needle still.

74 Closing the needle hole

75 Now that the tag is inserted and under the skin, the next step is closing the needle hole. This is done using
76 forceps and [Vetbond tissue adhesive](#) (Figure S12). Carefully pinch the hole closed with the forceps and apply
77 a couple of drops of vetbond on the hole. Be careful not to apply too much as it can get on the feathers and
78 make them hard. Once the hole stays closed on its own, release the forceps. It is best to do this while the
79 vetbond is still a little tacky and not stuck to the forceps. Then gently blow on the area to promote drying.
80 Once the vetbond is dry, use the tip of the plunger to arrange the feathers to cover the exposed area (the
81 lidocaine gel already applied to the bird helps with this and keeps the feathers in place). Check the location
82 of the tag in the neck by blowing the feathers in that area. Read the tag now that it is in the bird using the



Figure S10: Inserting the PIT tag while holding onto the needle with forceps to keep it in place.



Figure S11: PIT tag inserted under the skin. The needle hole is still visible.

83 reader and antenna to confirm the tag ID and that it is reading properly.

84 **List of materials**

- 85 • Tags: 8mm Passive Integrated Transponder tag (weight 0.034 g) from Biomark, [MiniHPT8 8.4 mm
86 × 1.4 mm, 134.2 kHz ISO FDX-B](https://www.biomark.com/pub/media/HPT8.pdf). Further documentation at [https://www.biomark.com/pub/media/
87 HPT8.pdf](https://www.biomark.com/pub/media/HPT8.pdf).
- 88 • N165 Needles
- 89 • MK165 Implanter



Figure S12: Applying Vetbond to the needle hole and closing it with forceps.



Figure S13: Needle insertion hole closed with Vetbond, waiting for glue to dry.

- 90 • Akorn Lidocaine hydrochloride jelly USP 2%
- 91 • Betadine antiseptic solution (povidone-iodine, 10%)
- 92 • Foam pad on which to perform the procedure
- 93 • Hand sanitizer
- 94 • Forceps - flat, no ridges, with blunted ends
- 95 • 70% ethyl alcohol
- 96 • Cotton swabs

- 97 • RFID readers and antennae (see Figure 1 of the main text)



Figure S14: Recaptured bird with implanted PIT tag (green hermit hummingbird in Costa Rica).

98 A narrated video of the procedure is available upon request.

99 **RFID recording station**

100 The 8 mm tags we used for Rufous Hummingbirds are not compatible with the protocol as described by
101 Bridge and Bonter (2011), but require a minor modification to the protocol. We used readers with a reading
102 scheme that reads 8 mm tags at 134.2 KHz following the ISO11785 protocol. The schematics for this variant
103 can be obtained upon request from [Dr. Eli Bridge](#).

104 **Sender-Receiver model description**

105 **Background**

106 We compiled records of bird relocations from four years in which we maintained RFID-equipped hummingbird
107 feeders and extracted movement information by tallying occasions on which an individual was recorded at
108 feeder i at time t and again at feeder j , $j \neq i$, at time t' , $t' > t$, within the same day. We chose to limit our
109 focus to movement that occurred within the same day to gain insight into hummingbird movements that
110 may be relevant to pollination. Additionally, we chose to sum the movements over the year in order to get
111 multiple measurements of movement between two feeders (one per year) that can more reasonably be treated
112 as exchangeable observations. If instead we sum over shorter periods of time, yielding multiple measurements
113 in a given year, measurements within the same year are unlikely to be exchangeable with measurements of

114 a different year, requiring a more complicated model. Instead, we effectively average movements over the
 115 flowering period of the primary nectar-producing plants. While we lose some information on differences
 116 between sexes, ages, and inter-individual differences in foraging behaviors by summing movements over the
 117 year, our objective was to model functional connectivity informed by hummingbird movements. Whether a
 118 given number of movements is made by many birds each making few movements or by few birds making many
 119 movements is not important in this endeavor. Because we only consider movements during the flowering
 120 period, this approach should reflect the potential for pollen flow among locations in the landscape.

121 We treated each feeder as a node in a graph (network) and modeled the edge weight (degree of connectivity
 122 between two nodes) of each edge in the graph. We denote λ_{ij} as the weight of the directed edge (in directed
 123 graphs, $\lambda_{ij} \neq \lambda_{ji}$) connecting node i to j and assume that the observed number of movements between two
 124 feeders in a given year, y_{ijk} , where $k = 1, 2, \dots, K$ indexes the year, was a random draw from a Poisson
 125 distribution with rate parameter λ_{ij} . Thus, in year k , when r_k out of the total R feeders were positioned
 126 and maintained on the landscape, there was a total of $n_k = r_k(r_k - 1)$ possible movements (because λ_{ii} is
 127 not defined), yielding $N = \sum_{k=1}^K n_k$ total observations.

128 Model description

129 Let $y_{ijk} \in \mathbb{N}$ be the number of movements detected between readers i and j by hummingbirds in year k ,
 130 where $i \neq j = 1, 2, \dots, R$, and R is the total number of feeders used (20 in total). Following Hoff (2005), we
 131 model the number of movements in a bilinear model where

$$\log(\lambda_{ijk}) = \mathbf{x}'_{ij}\beta + u_i + w_j + \gamma_{ij} + \log(b_k) + \log(d_k)$$

132 where β is a vector of dyad specific effects with \mathbf{x}_{ij} the vector of dyad-specific regressors for dyad $\{i, j\}$
 133 and ' denotes the matrix transpose. The effects u_i and w_j are the average effects of reader i as a “sender”
 134 (movements originating at feeder i) and “receiver” (movements ending at feeder i), respectively, and the
 135 term γ_{ij} is an average effect on movement for the pair of feeders $\{i, j\}$. Finally, b_k and d_k are offsets for the
 136 cumulative number of birds that had been implanted with RFID tags in year k and the number of days the
 137 readers were maintained in year k (respectively).

138 We assume there are multiple levels of dependence in these data. For example, movements coming from
 139 another location to feeder i may be correlated, and those leaving feeder i may also be correlated. Finally,
 140 movements within a dyad ($\{i, j\}$ pair) may be correlated. To induce dependence among observations that
 141 involve reader i , we assume

$$\begin{bmatrix} u_i \\ w_i \end{bmatrix} \sim \mathcal{N}(\mathbf{0}, \Sigma_{uw}),$$

$$\Sigma_{uw} = \begin{bmatrix} \sigma_u^2 & \sigma_{uw} \\ \sigma_{uw} & \sigma_w^2 \end{bmatrix},$$

such that observations that have a common sender or receiver may be correlated. Importantly, this allows for the potential that “good senders” may be “poor receivers”, so negative correlation is a possibility. While unlikely in our landscape scale study, this can allow for source-sink dynamics in the movements (Pulliam 1988). Finally, let

$$\begin{bmatrix} \gamma_{i,j} \\ \gamma_{j,i} \end{bmatrix} \sim \mathcal{N}(\mathbf{0}, \Sigma_\gamma),$$

$$\Sigma_\gamma = \begin{bmatrix} \sigma_\gamma^2 & \rho\sigma_\gamma^2 \\ \rho\sigma_\gamma^2 & \sigma_\gamma^2 \end{bmatrix},$$

where ρ is the correlation between the rate of movement from $i \rightarrow j$ and $j \rightarrow i$. These differ from standard random effects models because they allow for negative correlation of the observations within a dyad. For our purposes, this flexibility may help elucidate *traplining* foraging behaviors in which birds forage in a regular circuit among food sources (Feinsinger 1976). This could result in negative correlations within dyads if circuits tend to be directional (e.g., birds visit a circuit of meadows in a clockwise fashion).

151 Priors

We use weakly informative, $\mathcal{N}(0, 1)$ priors for all regression coefficients. These priors reflect the prior assumption that, with probability 0.95, the effect of an increase of 1 unit in any of the covariates will not result in more than a ~7-fold increase/decrease in the movement rate. They therefore constrain the HMC sampler to biologically reasonable parameter space, while remaining conservative because evidence in the data needs to be strong to pull the posterior away from zero.

For the variance components, we utilize a decomposition of the covariance matrices Σ_γ and Σ_{uw} in order to simplify prior specification and improve computation efficiency (Team 2021). In particular, let Ω be a correlation matrix and \mathbf{L} be the lower triangular Cholesky factor of Ω such that $\mathbf{LL}' = \Omega$. We put

160 a *Cholesky LKJ correlation* prior (Lewandowski, Kurowicka, and Joe 2009) on the matrices \mathbf{L}_γ and \mathbf{L}_{uw}
 161 (subscript notation following from above). For a $K \times K$ lower triangular Cholesky factor \mathbf{L} , the density
 162 $\pi(\mathbf{L} | \eta)$ for the prior is

$$\pi(\mathbf{L} | \eta) \propto \prod_{k=2}^K \mathbf{L}_{kk}^{K-k+2\eta-2}.$$

163 If $\eta = 1$, then the density is uniform over all correlation matrices of order K . We let $\eta = 5$ for both \mathbf{L}_γ and
 164 \mathbf{L}_{uw} , which forms a peak at the identity matrix (no correlation). This peak gets sharper as $\eta \rightarrow \infty$.

165 By putting a prior on the (Cholesky factor of the) correlation matrix, this allows a separate prior specifica-
 166 tion for the scale parameters for the multivariate normal distribution of the vectors $\begin{bmatrix} u_i & w_i \end{bmatrix}^T$, $i = 1, 2, \dots, R$
 167 and $\begin{bmatrix} \gamma_{ij} & \gamma_{ji} \end{bmatrix}^T$, $i = 1, 2, \dots, R$. For the scale parameters, we chose half-Normal(0,2) priors in order to
 168 maintain some flexibility while also constraining the parameter space to reasonable values (e.g., a log-effect
 169 size of 100 for a given feeder's random effect is not very reasonable). The summarized movement data and
 170 code for fitting this model can be found in the github repository [RUHU-movements](#). The raw data will be
 171 made publicly available on the [H. J. Andrews Data portal](#).

172 Supplementary analyses

173 Summaries of feeder use

174 It is possible that, due to high sucrose supplies, individual hummingbirds assumed defense of certain feeders
 175 and limited their movements away from the feeders. To check this possibility (though we do not believe
 176 this check can be considered a perfect assessment), we quantified the average number of hummingbirds using
 177 feeders in a given year and compared this to the total number of visits per feeder-day (number of days a feeder
 178 was present on the landscape). Based on prior research on territoriality in hummingbirds, if feeders present
 179 extremely valuable resources, we might expect increased territoriality at feeders compared to natural flower
 180 patches (Ewald and Carpenter 1978; Kodric-Brown and Brown 1978; Justino, Maruyama, and Oliveira 2012).
 181 With increased territoriality, we would expect the number of hummingbirds visiting a feeder to be largely
 182 decoupled from the total number of visits to that feeder (Figure S15a&b). Furthermore, we would expect
 183 that individual richness (number of birds recorded at a feeder) would be drastically greater than a diversity
 184 metric that weights richness by the evenness of visitation frequencies across individuals, which should tend
 185 towards 1 as a single dominant individual assumes control over the feeder. We therefore computed the
 186 Shannon-Weiner diversity of birds (diversity of individuals) for each feeder, $D_i = \exp \left\{ - \sum_{b=1}^{B_i} p_{ib} \log(p_{ib}) \right\}$,

187 $i = 1, 2, \dots, R$ indexes the feeder, $b = 1, 2, \dots, B_i$ indexes the bird recorded visiting feeder i , and p_{ib} is the
188 proportion of visits to feeder i that can be attributed to bird b .

189 In some cases, the number of visits to a feeder relative to others deviates from the number of birds using
190 that feeder relative to others (Figures S15a&b). The Shannon-Weiner diversity also diverges from individual
191 bird richness, indicating that one or two individuals compose the majority of visits to any one feeder. These
192 results, unsurprisingly, support the idea that feeders present a coveted (nearly unlimited) resource. However,
193 the deviation from the maximum value in the Shannon-Weiner diversities support that territoriality may
194 have maintained movement through the landscape by all but the most dominant hummingbirds.

195 Movements following competitive interactions

196 If competition among hummingbirds maintains movement through the landscape, we might expect that
197 birds would be more likely to move to another feeder following a visit to a busy feeder. To test this idea,
198 we quantified feeder use during ten-minute intervals over the four-year study period by tallying the number
199 of birds recorded at a feeder in each ten-minute window. We then fit a generalized linear mixed model to
200 the data on whether or not a bird moved from feeder i at time t to j at time t' , $t' > t$, using the number
201 of birds that visited feeder i in the ten-minute window into which time t falls. We additionally included a
202 random effect for the bird to account for inter-individual differences in movement propensity among birds.

203 We found little evidence that, on the whole, birds are more likely to move to another food resource
204 following competitive interactions. The estimated effect of the number of birds at a feeder in a ten-minute
205 window on the log-odds of movement was estimated to be $\hat{\beta} = -0.15$ ($SE_{\hat{\beta}} = 0.255$, $z = -0.578$, $P(Z >$
206 $|z|) = 0.563$). Birds appeared to have highly variable responses ($\hat{\sigma}_{\beta_1}^2 = 1.08$; Figure S16), supporting a
207 hierarchy in competitive dominance in which some birds were more competitive at feeders and forced other
208 birds away from feeders. However, we caution readers to the fact that we do not have detailed information
209 on the occasions on which birds were actually engaged in competitive interactions with other birds and can
210 only speculate that the number of birds at a feeder could be related to competition at the feeder.

211 Data summaries of birds that did not move

212 Of the 63 Rufous Hummingbirds that were relocated, 35 were not recorded moving among feeders. The
213 majority of these birds (31 of 35) were only recorded on a few occasions. Of the 4 (1 male, 3 females) that
214 had longer tenures in the system, all appear to have established territories around a center feeder, composing
215 the most visits to their preferred feeders of any other bird, though generally not the majority of all visits
216 (Table S1). Two of these birds (1 male, 1 female) were recorded at multiple feeders in the same year, but

²¹⁷ were not included in the movement data because they were not recorded moving among feeders in the same
²¹⁸ day (Table S1).

Table S1: Data on birds with long tenures on the landscape but were not recorded moving among feeders in any given day.

Bird ID	Sex	Year	Feeder	Feeder type	Proportion of visits
0EB27598596F0001	F	2017	M2_C	Center	0.318
25B27598596F0001	M	2016	CM_C	Center	0.840
3E727598596F0001	F	2017	LOM_C	Center	1.000
4FB27598596F0001	M	2016	LOM_C	Center	0.019
4FB27598596F0001	M	2016	M1_NE	Forest	0.010
82727598596F0001	F	2017	M2_C	Center	0.011
9CEBC199F0870001	U	2015	LOM_C	Center	0.662
9CF27598596F0001	F	2017	M2_C	Center	0.517
B3F27598596F0001	F	2016	LOM_C	Center	0.185
B3F27598596F0001	F	2016	M1_NE	Forest	0.010

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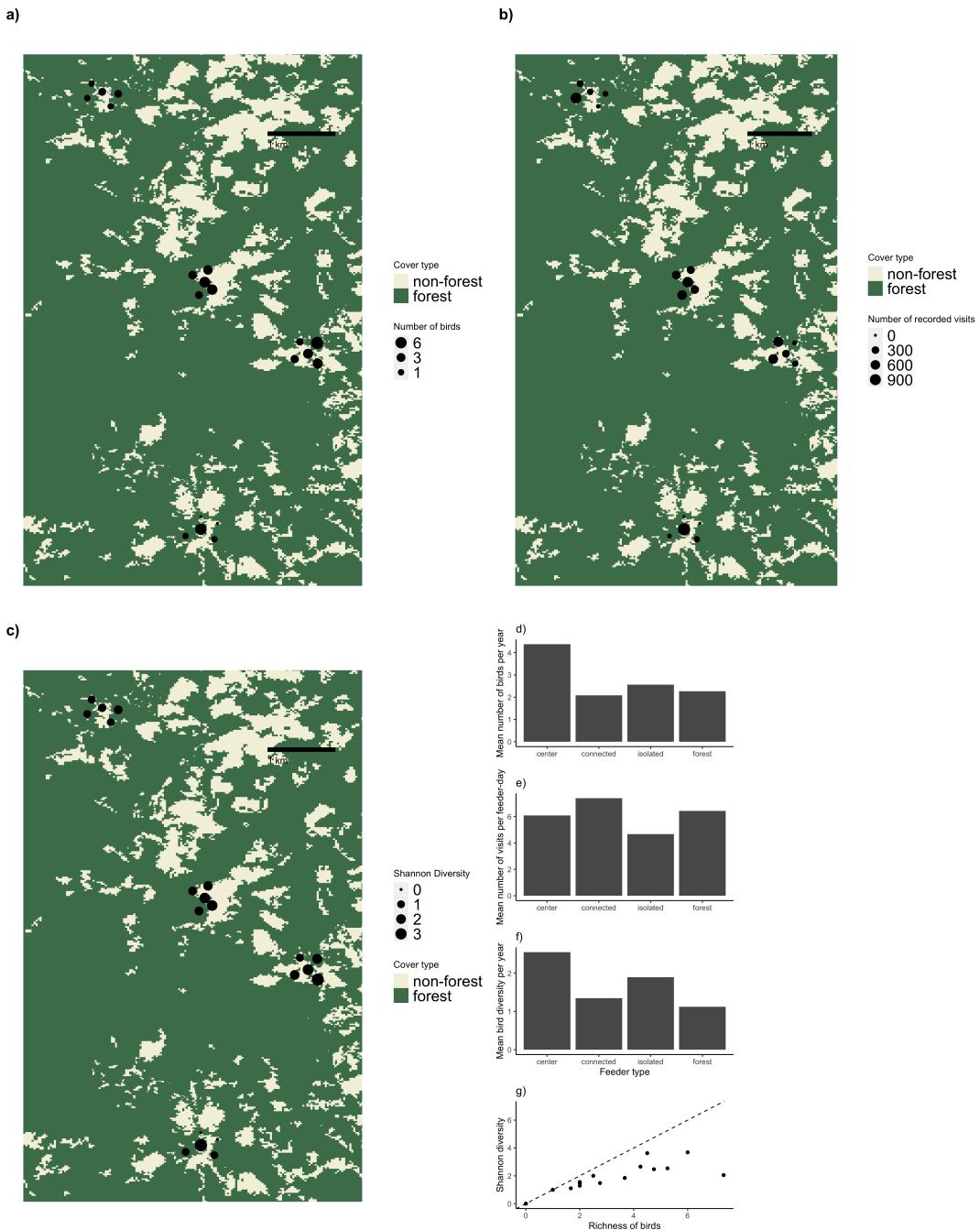


Figure S15: Summaries of feeder use over the four years of study. **a)** Visual representation of the average number of birds using each feeder over the years. **b)** Visual representation of the average number of separate visits to each feeder over the years. **c)** Visual representation of the Shannon-Weiner diversity of visits (diversity of individuals of the same species, *Selasphorus rufus*) to each feeder over the years. **d)** Average number of birds using the different feeder types ("treatments"), averaged over years for each feeder, then averaged over feeders belonging to a specific type. **e)** Average number of separate visits (records of birds spaced by at least 30 s) per feeder per day to different feeder types, averaged over years for feeders then over feeders in a given type. **f)** Average Shannon-Weiner diversity across feeder types, averaged over years and feeders. **g)** Relationship between individual bird richness and diversity of individuals at each feeder.

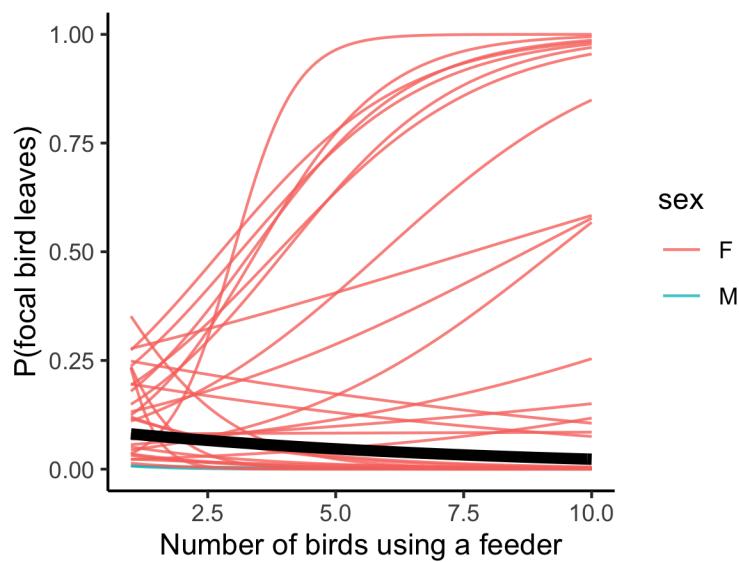


Figure S16: Estimated probability that a hummingbird was recorded moving to another feeder j as a function of the intensity of use (measured as number of birds recorded at a feeder in a ten minute window) at feeder i before moving from i to j . Each line represents the estimated curve for a different individual. The black line is the average effect of the intensity of feeder use on the probability of movement.