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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PIT tag implantation procedure

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

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

Figure S1: Customized banding station setup.

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

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

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

Inserting the needle and implanting the PIT tag

For the entire implant procedure, it will be very important for the person holding the bird to position their hand in a way that makes room for the implanter. This can be accomplished by the holder lifting up/holding away the area of their hand between their thumb and pointer finger (it can feel awkward while 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.

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

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

Preparing the plunger

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

Figure S4: Applying lidcaine gel to exposed skin.

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

Attaching the plunger and inserting the tag

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

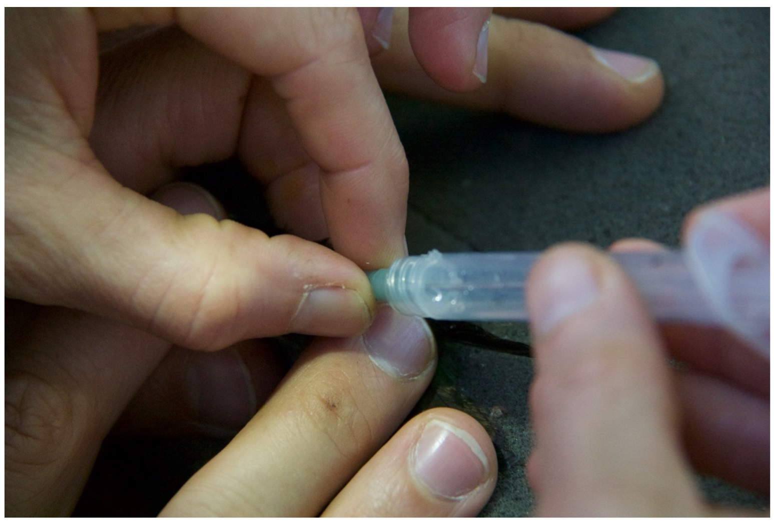

Figure S9: Attaching the plunger by screwing it onto the needle while keeping the needle still.

Closing the needle hole

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

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

List of materials

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

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

- 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).

A narrated video of the procedure is available upon request.

RFID recording station

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

Sender-Receiver model description

Background

We compiled records of bird relocations from four years in which we maintained RFID-equipped hummingbird feeders and extracted movement information by tallying occasions on which an individual was recorded at 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 focus to movement that occurred within the same day to gain insight into hummingbird movements that may be relevant to pollination. Additionally, we chose to sum the movements over the year in order to get multiple measurements of movement between two feeders (one per year) that can more reasonably be treated as exchangeable observations. If instead we sum over shorter periods of time, yielding multiple measurements in a given year, measurements within the same year are unlikely to be exchangeable with measurements of a different year, requiring a more complicated model. Instead, we effectively average movements over the flowering period of the primary nectar-producing plants. While we lose some information on differences between sexes, ages, and inter-individual differences in foraging behaviors by summing movements over the year, our objective was to model functional connectivity informed by hummingbird movements. Whether a given number of movements is made by many birds each making few movements or by few birds making many movements is not important in this endeavor. Because we only consider movements during the flowering period, this approach should reflect the potential for pollen flow among locations in the landscape.

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

Model description

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

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

where $\boldsymbol{\beta}$ is a vector of dyad specific effects with $\mathbf{x}_{ij}$ the vector of dyad-specific regressors for dyad $\{i, j\}$ and $'$ denotes the matrix transpose. The effects u_i and w_i are the average effects of reader i as a "sender" (movements originating at feeder i) and "receiver" (movements ending at feeder i), respectively, and the 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 cumulative number of birds that had been implanted with RFID tags in year k and the number of days the readers were maintained in year k (respectively).

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

$$\begin{bmatrix} u_i \\ w_i \end{bmatrix} \sim \mathcal{N}\left(\mathbf{0},\ \mathbf{\Sigma}_{uw}\right),$$

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

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

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

$$\mathbf{\Sigma}_\gamma = \begin{bmatrix} \sigma_\gamma^2 & \rho\sigma_\gamma^2 \\ \rho\sigma_\gamma^2 & \sigma_\gamma^2 \end{bmatrix},$$

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).

Priors

We use weakly informative, $\mathcal{N}(0, 1)$ priors for all regression coefficients. These priors relfect 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 $\mathbf{\Sigma}_\gamma$ and $\mathbf{\Sigma}_{uw}$ in order to simplify prior specification and improve computation efficiency (Team 2021). In particular, let $\mathbf{\Omega}$ be a correlation matrix and $\mathbf{L}$ be the lower triangular Cholesky factor of $\mathbf{\Omega}$ such that $\mathbf{L}\mathbf{L}' = \mathbf{\Omega}$. We put a *Cholesky LKJ correlation* prior (Lewandowski, Kurowicka, and Joe 2009) on the matrices $\mathbf{L}_\gamma$ and $\mathbf{L}_{uw}$ (subscript notation following from above). For a $K \times K$ lower triangular Cholesky factor $\mathbf{L}$, the density $\pi(\mathbf{L} \mid \eta)$ for the prior is

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

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

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

Supplementary analyses

Summaries of feeder use

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

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

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

Movements following competitive interactions

If competition among hummingbirds maintains movement through the landscape, we might expect that birds would be more likely to move to another feeder following a visit to a busy feeder. To test this idea, we quantified feeder use during ten-minute intervals over the four-year study period by tallying the number of birds recorded at a feeder in each ten-minute window. We then fit a generalized linear mixed model to 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 of birds that visited feeder i in the ten-minute window into which time t falls. We additionally included a random effect for the bird to account for inter-individual differences in movement propensity among birds.

We found little evidence that birds are more likely to move to another food resource following competitive interactions. The estimated effect of the number of birds at a feeder in a ten-minute window on the log-odds of movement was estimated to be $\hat{\beta} = -0.06$ ($z = -1.13$, $P(Z > |z|) = 0.257$). However, we caution readers to the fact that we do not have detailed information on the occasions on which birds were actually engaged in competitive interactions with other birds and can only speculate that the number of birds at a feeder could be related to competition at the feeder.

Data summaries of birds that did not move

Of the 63 Rufous Hummingbirds that were relocated, 35 were not recorded moving among feeders. The majority of these birds (31 of 35) were only recorded on a few occasions. Of the 4 (1 male, 3 females) that had longer tenures in the system, all appear to have established territories around a center feeder, composing the most visits to their preferred feeders of any other bird, though generally not the majority of all visits (Table S1). Two of these birds (1 male, 1 female) were recorded at multiple feeders in the same year, but were not included in the movement data because they were not recorded moving among feeders in the same 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
11F27598596F0001	M	2016	LOM_C	Center	0.190
11F27598596F0001	M	2017	M1_C	Center	0.437
11F27598596F0001	M	2016	M1_NE	Forest	0.010
9CF27598596F0001	F	2017	M2_C	Center	0.517
B3F27598596F0001	F	2016	LOM_C	Center	0.134
B3F27598596F0001	F	2016	M1_NE	Forest	0.010

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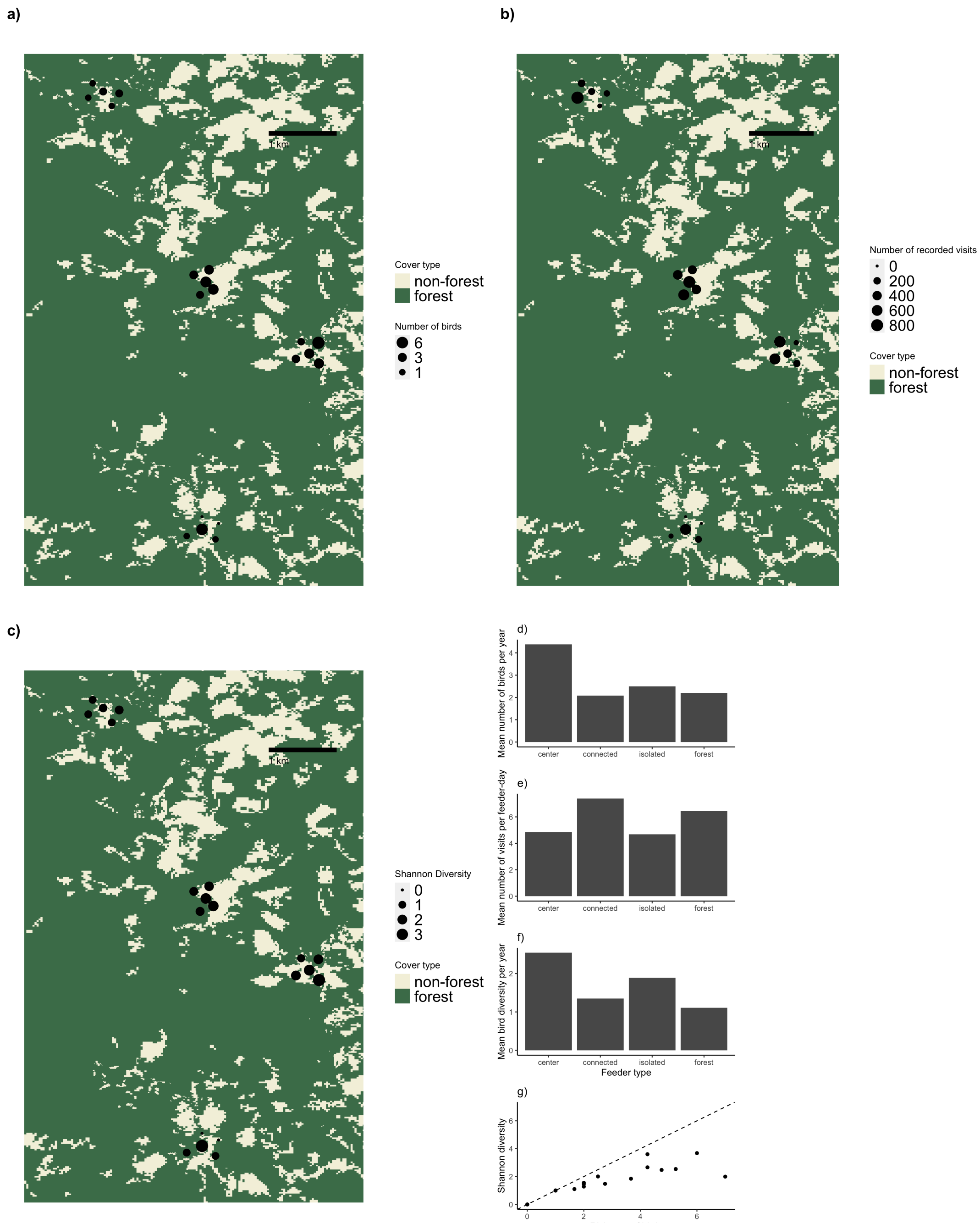

Figure S15: Summaries of feeder use over the four years of study. **a)** Visual representation of the average number of birds using each feeder over the years. **b)** Visual representation of the average number of separate visits to each feeder over the years. **c)** Visual representation of the Shannon-Weiner 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.