**An evidence-based approach to conceptual model development applied to understanding mechanisms underlying area sensitivity in forest songbirds**

Eliza M. Grames and Chris S. Elphick

*University of Connecticut, Department of Ecology and Evolutionary Biology, Storrs, CT 06269*

**Abstract**

In order to explain variation in the observed patterns of edge and area sensitivity, researchers have proposed and tested potential underlying mechanisms such as nest predation, brood parasitism, food abundance, pairing success, microclimate changes, and other factors that may affect demographic parameters. Mechanisms that have been proposed and tested each explain some variation in sensitivity on their own, however, studies typically only test one or two mechanisms in the same system.To fully understand variation in edge and area sensitivity, researchers need to consider both the direct and indirect relationships between all potential mechanisms and other factors that may mediate these relationships. We aim to develop a conceptual model of mechanisms underlying edge and area sensitivity using a systematic approach to reviewing the literature and identifying links between potential mechanisms. We will search bibliographic databases, thesis and dissertation databases, and organizational websites to identify studies testing mechanisms of edge and area sensitivity. For each included study, we will extract the hypotheses tested by authors and their inferred causal relationship. We will then combine all of the tested hypotheses into a directed acyclic graph containing all hypotheses from all studies. With the resulting “metaDAG”, we will use network analysis to identify trends in research on this topic and identify knowledge gaps and clusters.

**1. Background**

When the theory of island biogeography (MacArthur and Wilson 1967) was first applied to habitat fragmentation (Galli et al. 1976, Haila 2002), it sparked decades of research in which hundreds of researchers observed the same pattern—many species exhibit area sensitivity, with decreased density in small patches. With an increasing number of studies, it has become clear that studies of the same species can produce conflicting results and that the pattern is not consistent across taxa, habitat types, or studies. Most of these studies describe patterns and trends associated with patch size, rather than looking at the underlying mechanisms of area sensitivity that could explain heterogeneity in species-area relationships and area sensitivity (Bayard and Elphick 2010). When studies do consider potential underlying mechanisms in order to explain variation in observed area sensitivity, they typically focus on only one or two mechanisms and neglect to consider mediating variables or interactions between mechanisms. For mechanisms that have received the most research attention, findings and researcher interpretations are not consistent across studies or systems, indicating either gaps in the literature or potentially species-specific responses to fragmentation and patch size that cannot be generalized across taxa.

Low reproductive success is frequently proposed as a driving mechanism of area sensitivity because it affects both recruitment of new individuals and retention of existing individuals in a population. Small habitat patches with low reproductive success are often population sinks with low offspring recruitment that reduces population density (Pulliam 1988). Although adult songbirds typically exhibit high site fidelity, reproductive failure at a site can cause them not to return to a territory for subsequent breeding events (Porneluzi 2003). Reproductive failure can occur at any point during the breeding season, from territory establishment and mate attraction to nestling growth and fledgling survival. Many studies on area sensitive species have focused on nest predation (e.g. Donovan et al. 1997, Zanette and Jenkins 2000, Vergara and Simonetti 2003, Richmond et al. 2011) and brood parasitism (e.g. Davidson and Knight 2001, Hannon et al. 2009, Falk et al. 2011) as driving causes of reproductive failure, with fewer studies investigating the role of food abundance (e.g. Burke and Nol 1998, Huhta et al. 1998, Zanette et al. 2000, Boulton et al. 2008, Richmond et al. 2011), other variables, or interactions between variables. If there is covariation in reproductive success and patch size, any factors that affect reproductive success could explain variation in area sensitivity.

Low habitat quality in small habitat patches could decrease population density by reducing the number of available territories. In low quality breeding habitat, territory sizes may be larger to compensate for reduced resources, decreasing the number of territories available to male ovenbirds (*Seiurus aurocapilla*) arriving in temperate forests (Ortega and Capen 1999, Streby et al. 2013). Arrival time in patches could also indicate habitat quality because males that arrive early are able to establish territories in the highest quality habitat. Studies on pied flycatchers (*Ficedula hypoleuca*) have documented that males arriving earlier in the breeding season establish territories in large habitat patches, where females also arrive earlier than to small patches (Huhta et al. 1998, Huhta and Jokimaki 2001). These studies suggest that females prefer territories of males nesting in large habitat patches because they are of higher quality and will result in greater reproductive success. This relationship can be measured through male pairing success along a patch size gradient. In many cases, male pairing success has a positive relationship with patch size, distance from edge of the patch, and the density of territorial males in a fragment (e.g. Hagan et al. 1996, Huhta et al. 1998, Burke and Nol 2000, Huhta and Jokimaki 2001, Robles et al. 2008). Potential reasons for the relationship between patch size and pairing success may be that females are selecting male territories with higher food abundance (Ortega and Capen 1999) and suitable nest sites (Horn et al. 1995), that females exhibit conspecific attraction, or encounter large patches more frequently (Huhta et al. 1998, Robles et al. 2008).

Once a pair establishes a nest, it is subject to predation and brood parasitism, both of which frequently result in reproductive failure (Hannon et al. 2009). Nest predation rates are often higher in small patches (Arango-Velez and Kattan 1997, Zanette and Jenkins 2000, Richmond et al. 2011) and patches with a high ratio of edge habitat to core habitat (Hoover et al. 1995). Within patches, regardless of size, several studies have shown a negative relationship between nest predation rates and distance from patch edge (Wilcove 1985, Andren and Angelstam 1988, Donovan et al. 1997) which is magnified for ground nesting species (Arango-Velez and Kattan 1997, Burke and Nol 2000). This relationship may be explained by differences in predator assemblage in edge habitat when compared to core habitat. In North American temperate forests, mammalian predator abundance tends to be higher in small fragments and edge habitats than core habitat, especially for mesopredators such as raccoons (*Procyon lotor*) and opossums (*Didelphis virginiana*) (Hoover et al. 1995, Disney et al. 2008). Microclimate differences between edge habitat and core habitat alter vegetation structure, which can also increase snake and avian predator abundance (Zanette and Jenkins 2000, Chalfoun et al. 2002, Sperry et al. 2009, Richmond et al. 2011). These factors suggest that edge effects may be responsible for increased nest predation in small patches.

Brood parasitism rates tend to vary similarly to nest predation with patch size, although landscape factors play a larger role. The proportion of nesting pairs parasitized by brown-headed cowbirds (*Molothrus ater*) is higher in small forest patches than large patches of riparian forest (Davidson and Knight 2001), especially when the surrounding landscape is cropland or other habitat that is suitable foraging habitat for adult cowbirds (Falk et al. 2011, Lloyd et al. 2006). Nests that are parasitized by cowbirds have higher rates of nest predation at the nestling stage than unparasitized nests, likely due to begging by cowbird chicks that attracts nest predators (Hannon et al. 2009). Low food abundance may exacerbate this effect both by increasing the rate of begging and because cowbird chick demand for food increases the amount of time adults must spend foraging which leaves nests exposed to predation with no parental defense (Boulton et al. 2008). Although several studies (e.g. Huhta et al. 1998, Zanette et al. 2000, Boulton et al. 2008, Richmond et al. 2011) have considered food abundance as a potential driver of area sensitivity, its interactions with other mechanisms like nest predation and brood parasitism remain understudied.

Despite many studies considering mechanisms of area sensitivity in isolation, there is no consensus on which mechanisms play the largest role in species’ responses to fragmentation or on how the mechanisms interact. Even though most studies have focused on nest predation to some extent, there is no strong signal in what drives the relationship between patch size and nest predation rates. Studies have suggested that the effects of fragmentation on nest predation vary among nesting guilds (Arango-Velez and Kattan 1997, Lloyd et al. 2006) or are mediated by confounding factors not considered in the study, such as microclimate variables or adjacent matrix habitat type (Huhta et al. 1998, Ortega and Capen 1999, Fauth et al. 2000, Huhta and Jokimaki 2001, Davidson and Knight 2001). Similarly, unmeasured characteristics of vegetation structure and understory plant density may mediate the effect of nest predation, especially for ground nesting species (Hagan et al. 1996, Richmond et al. 2011). Given the amount of heterogeneity in the design and results of studies on mechanisms underlying area sensitivity, there is no clear pattern as to which processes matter most in determining species’ responses to patch size and fragmentation or how processes affect species differently. Because of the large number of studies that have considered a subset of potential mechanisms, however, it is possible to explore the problem using evidence synthesis techniques.

To identify the potential mechanisms and pathways that lead from fragmentation and decreased patch size to decreased densities of forest interior songbirds, we will develop an evidence-based conceptual model of potential mechanisms underlying area sensitivity. We will conduct a systematic review of the literature to identify studies that propose and test potential mechanisms and will extract the associated causal pathways to build an evidence-based directed acyclic graph (DAG) of all potential pathways. This “metaDAG” will be reduced to the core conceptual model through a transitive reduction to identify linked pathways across studies that each contain part of the overall mechanistic model and can lead to a more complete understanding when synthesized.

**1.1. Stakeholder engagement**

This project arose out of discussion with the University of Connecticut Bird Lab group about an early draft of a dissertation chapter by EMG that presented a narrative summary and conceptual model of proposed mechanisms, but was not based on principles of systematic review. Following the group discussion about lack of reproducibility in the process leading to the original conceptual model, EMG ad CSE identified a systematic way to develop a conceptual model on the same topic that was based on systematic review and structured development of causal models, as opposed to ad hoc methods that are typically employed. Members of EMG’s dissertation committee approved the preliminary plan for the project protocol in her dissertation proposal.

**2. Objective of the review**

**2.1. Objective**

We will identify studies that propose and test causal pathways leading from forest fragmentation and/or patch size to reduced density of forest interior songbird populations to build an evidence-based conceptual model of mechanisms underlying area sensitivity. This model will help us better understand and explain variation in area sensitivity and identify priority pathways to target for conservation interventions.

**2.2. Definitions of the question components**

To identify our question components, we are using the framework recommended by Johnson and Hennessy (2019) where moderator variables are explicitly considered at the outset of the project.

*Time*: We will only include studies that take place during the breeding season of the species studied, as most songbirds are restricted in their movement by territorial boundaries that are much smaller than winter home ranges (Morganti et al. 2017). This restriction on movement makes it easier to infer that processes operating at the local scale affect the population in a study without knowing individual identity, as non-breeding season studies could be capturing processes external to the study system.

*Outcome*: We will include studies that measure population density, abundance, or occupancy. We will also include studies that document population processes or responses that could affect population size, such as emigration.

*Population*: We will restrict the organisms studied to only forest songbirds (order Passeriformes).

*Intervention*: We are interested in comparisons of area sensitivity in forest patches of different sizes or across a gradient of fragmentation, such as in fragmented landscapes. We will include studies that contain any metric of fragmentation selected by the original authors, such as edge density or distance to edge.

*Comparator*: To be included, studies must contain a comparison that assesses the effects of patch size or distance to edge. To have a comparison, a study does not necessarily require multiple study sites; a study of nest predator activity with distance to edge would be included if multiple distances are compared.

*Space*: We will include studies that are conducted in boreal or temperate forests in North America. This does not include the tropical and subtropical forests of the Caribbean, Mexico, or Central America.

*Moderators*: Although the purpose of our systematic review is largely to identify moderator variables, we assume that the identified variables will be influenced by the taxa studied, geographic location where the study took place, and the type of matrix surrounding the forest patch.

**3. Methods**

**3.1. Searches**

*3.1.1. Search strategy*

To retrieve studies for our systematic review, we will search based on the title, abstract, and keywords in a set of bibliographic databases that contain ecological studies. To retrieve gray literature, we will also search government research databases, thesis databases, and data repositories. Because trial registries are not commonly used in ecology, we will not search them. Instead, we will search two pre-print servers and the Open Science Framework registry for unpublished studies. For all studies that meet our inclusion criteria or for relevant review articles that we retrieve, we will automatically add their reference lists to the set of articles for screening.

For platforms and databases that allow truncation within parentheses, we will use truncated terms if word stems are at least four characters. For other databases, we will use full phrases within quotes. We will use the R package litsearchr (Grames et al. 2019, Grames et al. 2020) to remove redundant search terms for all searches. For databases with limited search capability, we will modify our search string to the key terms and document the search string used.

Because some of the databases we will search do not have an option for searching only the title, abstract, and keywords and also include other fields (e.g. authors and references), we will re-apply our search terms to the title, abstract, and keywords fields in our deduplicated database of search results. Any articles that do not contain our search terms in these fields will be removed without manual oversight as they would not match our search strategy and would be a byproduct of the databases used.

*3.1.2. Search string*

We used litsearchr to generate our search string based on output of naive searches. For our naive search string, we developed concept categories for our time, outcome, population, intervention, and space question components (Table S1). For the space component, we did not include the geographic aspect as it would unnecessarily restrict our search because place names are unlikely to appear in the title, abstract, and keywords. We did not include the comparator component as it is implicit in the intervention and did not include categories for moderator variables.

We conducted our naive search in Scopus (1788-2020) and on Web of Science in the BIOSIS Citation Index (1926-2020) and in Zoological Record (1864-2020). We searched in the title, abstract, and keywords on Scopus and in the “Topic” field for databases on Web of Science. We placed no further restrictions on our search. Our search resulted in 1065 articles from Scopus (330), BIOSIS Citation Index (279), and Zoological Record (456). After removing duplicate articles, we had 645 unique articles remaining which were used to identify search terms with litsearchr.

We followed the default methods for litsearchr, which resulted in 424 search terms which EMG manually reviewed for inclusion in one of the question components used for our naive search. The naive search string components were incorporated into the final search (Table S2), which removed many of the space terms identified by litsearchr since they were redundant to “forest” and other one-word synonyms indicating forest habitats. After estimating the comprehensiveness of our search (see 3.1.5), we merged the concept categories for time and population outcome.

*3.1.3. Languages*

Because we are interested in studies conducted in North American temperate and boreal forests, we will search in both English and French to capture studies conducted in the United States and Canada.

*3.1.4. Bibliographic databases and gray literature sources*

We will search bibliographic databases, thesis and dissertation databases, governmental publications, data repositories, pre-print servers, and an organization website containing historical bird research (Table S3).

*3.1.5. Assessing the comprehensiveness of the search*

To determine if our search is able to retrieve articles known to be relevant to the topic, we checked our search string against a list of benchmark articles (Table S4) from papers included in a related synthesis (Archer et al. 2019), for forest habitat papers from an earlier meta-analysis (Bender et al. 1998), and the underlying dataset from a systematic map (Bayard and Elphick 2010). For all three sources, we only included benchmark articles that meet our population (forest passerines) and time (breeding season) criteria, though we did not restrict benchmark articles to North America because our search terms do not include this restriction and we would expect articles from outside North America to be relevant if they took place within North America. We first checked to see which benchmark articles were indexed in Scopus, BIOSIS Citation Index, and Zoological Record; any articles that were indexed were treated as part of the gold standard set. Of the 57 benchmark articles, the only one not indexed was Nilsson (1977). We ran our search in the same databases and checked the recall of our search with litsearchr. We checked any gold standard articles that were not retrieved against our search string to determine which question component was not met. We then identified potential keywords for each of our question components from the missing gold standard article title, abstract, and keywords to determine which additional terms should be added to our final search string. These additional terms are indicated in bold font in Table S2.

*3.1.6. Search update*

If the review takes more than two years to complete, we will redo our search to retrieve newly published studies.

**3.2. Article screening and study inclusion criteria**

*3.2.1. Screening strategy*

To assess if articles are relevant to the review, we will screen all deduplicated articles first by title alone to exclude obviously irrelevant articles (e.g. those where the title clearly indicates the study is not on passerines or does not take place in North America). This initial screen will use text mining to flag articles on the wrong taxa or location; any articles flagged in this process will be manually reviewed to ensure nothing is accidentally omitted. We will then repeat this partially automated process to review abstracts by first flagging irrelevant articles and then manually verifying whether they should be excluded.

*3.2.2. Consistency checking*

Because intercoder reliability is blind to direction of error and is not appropriate when applied to screeners with different levels of experience, we will instead use false positive and false negative screening rates evaluated by a third party to check consistency. EMG and a third researcher (to be determined) will each screen a random subset of 618 articles and conflicts will be resolved by a third party and discussed by all reviewers to clarify criteria (see below). We used the power.p.test in the R package pwr (Champely 2020) to calculate that this sample size is necessary to determine if reviewers have a false negative screening rate of greater than 0.1 which would be unsatisfactory. If a reviewer has a satisfactory false negative screening rate, they will continue to screen articles singly; if not, reviewers will continue to screen in duplicate with periodic checks to assess if either has reached a satisfactory error rate. .

When all articles have been screened, we will use topic modeling to cluster articles based on text similarity. Any articles that are highly similar to included articles based on distribution of text similarities, but were rejected by a single screener, will be reviewed by a second screener and conflicts will be resolved as before.

*3.2.3. Inclusion criteria*

To meet our inclusion criteria, a study must match our time, outcome, population, intervention (and the implicit comparator), and space components. This means a study must: 1) take place during the breeding season, 2) measure population density or processes that affect density, 3) be conducted on wild passerines, 4) measure patch size or fragmentation in some form, and 5) take place in temperate or boreal forests of North America. Our third eligibility criteria excludes artificial nest predation experiments, but not nest box studies.

*3.2.4. Reasons for exclusion*

We will provide a reason for articles excluded at all stages, including title screening which will be flagged with the term used to exclude them automatically.

**3.3. Critical appraisal**

We will not perform critical appraisal on included studies, as the purpose of this synthesis is to extract potential causal relationships between variables, not to conduct a narrative or quantitative synthesis of results.

**3.4. Data extraction**

*3.4.1. Meta-data extraction and coding strategy*

Because the pathways identified may differ with geographic location, matrix surrounding a forest patch, and taxa studied, we will code each included article for these variables as metadata. We will extract geographic location using the latitude and longitude of the central point of study locations; if no latitude or longitude is provided by the study authors, we will approximate the latitude and longitude based on place names included in the study. We will record the matrix type(s) reported by the study authors, if described. If no matrix type(s) are reported, we will record this as missing data. We will record all focal forest bird species included in a study; for example, if a study considers brown-headed cowbird brood parasitism of ovenbird and wood thrush nests, we will record the focal taxa as ovenbird and wood thrush, since cowbird behavior is a potential process, not a focal species.

We will also track aspects of study design that could influence which pathways are identified. We will record the metric of patch size or fragmentation used by a study, as reported by the authors. Although we do not know what the full list of metrics will be, we anticipate measures such as edge:area ratios, patch size, habitat islands compared to contiguous habitat, or distance to edge.

*3.4.2. Data extraction strategy*

We will combine full text screening and data extraction to make the process more efficient. When an article meets inclusion criteria at the full text stage, we will extract any tested pathways described in the study objectives or methods. We will also extract hypothesized and post hoc explanations for observed patterns from the discussion section. Hypothesized and post hoc explanations will be labeled as such in the final model unless they were tested in a different study.

*3.4.3. Approaches to missing data*

Because it is impossible to know if authors tested hypotheses and did not report them in a paper without contacting every author to confirm they did not omit data, we will assume that each paper includes all pathways that were considered. Meta-data may be missing, in which case it will simply be marked as missing and we will not attempt to retrieve it since it will not affect the final model.

*3.4.4. Consistency checking*

Because we are combining full text screening and data extraction, we will check consistency in extracting pathways from any articles that are included in the set of 618 articles screened in duplicate. For any articles where the pathways identified are different, reviewers will revisit the article, discuss their reasoning to prevent future errors, and resolve the pathways by consensus. We will not perform a quantitative analysis of consistency for these articles since path extraction, particularly from discussion sections, results in subjective, qualitative data not amenable to analysis.

*3.4.5. Potential effect modifiers/reasons for heterogeneity*

We will use the meta-data described above to identify any differences in final model structure using subgroups by taxa, geographic location, matrix type, and metric of fragmentation. Because our taxa classification encompasses both single species studies and community studies, we will treat these as different subgroups. For single species studies, we will also construct subgroup models at the family level. Because geographic location is a continuous measure of latitude and longitude, we will look for naturally occurring clusters of studies to create artificial geographic subgroups (e.g. “northeastern US”).

**3.5. Data synthesis and presentation**

*3.5.1. Narrative synthesis strategy*

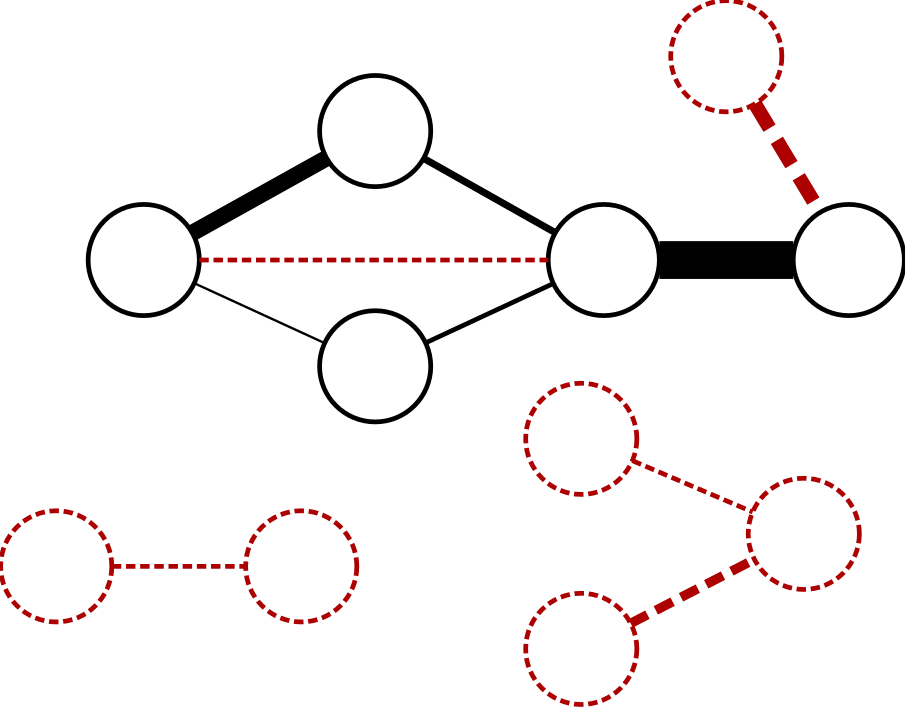
We will describe common themes identified across studies and will discuss how pathways may interact to produce different patterns of species abundance and occupancy in fragmented landscapes.

*3.5.2. Quantitative synthesis strategy*

We will not perform any quantitative analysis in this synthesis, however, a follow-up study using the conceptual model as the basis for a meta-analytic structural equation model has been proposed by the authors.

*3.5.3. Qualitative synthesis strategy*

Taking all of the tested and hypothesized causal pathways extracted from full texts, we will build a series of disconnected directed acyclic graphs (DAGs) for each study. We will then combine all of these separate DAGs into a “metaDAG” where links between disconnected nodes can be identified. Because some studies may have tested pathways that ignore intermediate steps that other studies have considered, we will perform a transitive reduction on the metaDAG to remove redundant pathways. For example, if one study considered the pathway A > C and another considered A > B > C, we will remove the direct pathway from A > C because it bypasses process B. We will also remove modular networks that do not connect to the central metaDAG and any exogenous nodes that cannot be traced back to a metric of fragmentation.

**Figure 1.** Example metaDAG illustrating modular networks, exogenous nodes, and paths that will be removed by a transitive reduction. Paths and nodes that will be removed are shown with red dashed lines and the final DAG used for interpretation is shown in solid black lines. Thickness of edges between nodes indicates the number of studies in which the pathway was tested.

*3.5.4. Assessment of risk of publication bias*

Because we are not extracting quantitative effect sizes, we are unable to use funnel plots to assess risk of publication bias. In lieu of effect sizes, we will construct subgroup DAGs for paths that were tested (extracted from the methods section) and those that were post-hoc explanations or hypotheses (extracted from the discussion section) to assess if there is bias towards studying or publishing certain pathways. We will also construct subgroup DAGs for grey literature (e.g. theses and dissertations) and published literature to check for publication bias towards certain pathways.

*3.5.5. Knowledge gap identification strategy*

We will identify knowledge gaps based on the number of studies that have tested pathways, as indicated by the thickness of edges between nodes (Figure 1). Pathways and modular components of the network that have received relatively little attention will be identified as gaps in the literature that merit additional research. Similarly, any paths in the network that have only been hypothesized but not tested represent knowledge gaps.

*3.5.7. Demonstrating procedural independence*

If during the screening process any reviewer identifies a conflict of interest with the authors of the article, they will skip that article and another reviewer will screen it for inclusion.

**4. Declarations**

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**Table S1.** Naive search string used to retrieve results for identifying new search terms with the R package litsearchr.

|  |  |
| --- | --- |
| **Question component** | **Naive search terms** |
| Time | (breed\* OR reproduct\* OR nest\* OR fledg\* OR territor\*) |
|  | AND |
| Outcome | ((population W/1 (densit\* OR “size” OR abundan\*)) OR occupanc\* OR “area sensitiv\*”) |
|  | AND |
| Population | (passeri\* OR songbird\* OR bird\* OR warbler\* OR thrush\* OR vireo\* OR nuthatch\* OR kinglet\* OR flycatch\* OR tanager\*) |
|  | AND |
| Intervention | (fragment\* OR “patch size” OR “area sensitiv\*” OR remnant\*) |
|  | AND |
| Space | (forest\* OR woodl\* OR deciduous OR conifer\* OR broadleaf) |

**Table S2.** Full search string. Bold terms indicate terms that were added as a result of checking the comprehensiveness of our search string.

|  |  |
| --- | --- |
| **Question component** | **Search terms** |
| Time | ((("reproductive success" OR "fledging success" OR "reproductive performance" OR "pairing success" OR "parasitism rates" OR "provisioning rates" OR "reduced fecundity" OR "singing males" OR "territorial males" OR "territory density" OR "territory occupancy" OR "ground nests" OR "young fledged" OR breeding OR reproduction OR nesting OR fledgling) |
|  | OR |
| Outcome | ("imperfect detection" OR "population density" OR "population persistence" OR "detection probability" OR "local extinction" OR "total number" OR "population status" OR "remaining populations" OR "adult mortality" OR "area-sensitive species" OR "population dynamics" OR "population growth" OR "population estimate" OR "breeding population" OR "total population" OR "demographic parameters" OR "density increased" OR "population sizes" OR "wildlife population" OR "higher density" OR "highest density" OR "effective population" OR "population trend" OR "lower density" OR "occupied patch" OR "small population" OR "population sinks" OR "population viability" OR "relative density" OR "population decline" OR "local population" OR "population change" OR "species increased" OR "species occurrence" OR "stable population" OR "species present" OR "population model" OR "survival rates" OR abundance OR "area sensitive" OR "area sensitivity" OR occupancy **OR “point count” OR survivorship OR "species composition"**)) |
|  | AND |
| Population | ("forest interior species" OR "avian responses" OR "avian species" OR "dendroica cerulea" OR "dumetella carolinensis" OR "hylocichla mustelina" OR "oporornis formosus" OR "piranga olivacea" OR "seiurus aurocapilla" OR "seiurus aurocapillus" OR "sensitive species" OR "setophaga chrysoparia" OR "singing males" OR "wilsonia citrina" OR "young fledged" OR passerine OR passeriformes OR bird OR warbler OR thrush OR vireo OR nuthatch OR kinglet OR flycatcher OR tanager **OR "avian community" OR chickadee OR wren OR veery**) |
|  | AND |
| Intervention | ("landscape management" OR "vegetation structure" OR "island biogeography" OR "agricultural landscape" OR "continuous forest" OR "landscape metrics" OR "larger patches" OR "smaller patches" OR "forest patch" OR "habitat amount" OR "landscape composition" OR "total forest" OR "forest cover" OR "forest structure" OR "forested areas" OR "forest opening" OR "large forest" OR "habitat alteration" OR "habitat change" OR "habitat configuration" OR "habitat degradation" OR "habitat disturbance" OR "habitat heterogeneity" OR "habitat patch" OR "habitat quality" OR "habitat requirement" OR "heterogeneous landscape" OR "forest edges" OR "landscape attributes" OR "landscape characteristics" OR "landscape context" OR "landscape ecology" OR "landscape effects" OR "landscape features" OR "landscape level" OR "landscape pattern" OR "landscape scale" OR "landscape structure" OR "landscape variable" OR "large areas" OR "large patches" OR "large tracts" OR "natural disturbance" OR "occupied patch" OR "intact forest" OR "patch isolation" OR "forest stand" OR "forest tract" OR "patch occupancy" OR "patch scale" OR "quality habitat" OR "sensitive species" OR "small patch" OR "small woodlots" OR "spatial configuration" OR "surrounding landscape" OR "urbanizing landscape" OR "urban landscape" OR "woodland patch" OR fragment OR remnant OR "patch size" OR "area sensitive" **OR "forest corridor" OR "forest area" OR "woodland area" OR "woodlot area" OR "grove size" OR "habitat island" OR "habitat area" OR "area requirement" OR "forest island" OR "forest size” OR "small forest"**) |
|  | AND |
| Space | ("canopy cover" OR forest OR woodland OR woodlot OR broadleaf OR coniferous OR deciduous)) |

**Table S3.** Platforms and databases to be searched, including type of database and the years of access. A \* indicates databases for which we will use the modified search string (“forest fragmentation” AND bird) and \*\* indicates a database in which we will only search “forest fragmentation” because of constraints on search functionality in these databases. The ‡ symbol indicates databases which will be searched after completing full text screening because results need to be manually screened in place due to the inability to export results from the database.

|  |  |  |  |
| --- | --- | --- | --- |
| **Type** | **Platform** | **Database** | **Years** |
| Bibliographic | Web of Science | BIOSIS Citation Index  Zoological Record | 1926-2020  1864-2020 |
| Bibliographic | Scopus | Scopus | 1788-2020 |
| Bibliographic | EBSCO | Academic Search Premier  Agricola  OpenDissertations  CAB Abstracts | 1887-2020  1970-2020  1597-2020  1973-2020 |
| Thesis | NDLTD | Networked Digital Library of Theses and Dissertations | 1970-2020 |
| Thesis | OATD | Open Access Theses and Dissertations | 1597-2020 |
| Thesis | OpenThesis | OpenThesis | 1602-2020 |
| Thesis | Library and Archives Canada | Theses Canada\*‡ | 1965-2020 |
| Thesis | ProQuest | ProQuest Dissertations & Theses |  |
| Governmental | Science.gov |  | N/A |
| Repositories |  | Dryad\*  Zenodo \*\* | N/A  N/A |
| Pre-print servers |  | bioRxiv\*  EcoEvoRxiv \*‡ | 2014-2020  2018-2020 |
| Organizations | University of New Mexico | Searchable Ornithological Research Archive\*‡ | N/A |

**Table S4.** Benchmark articles used to evaluate the comprehensiveness of the search strategy. A \* indicates that the article was not indexed. All indexed articles were retrieved after adding missing search terms (Table S2).

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| --- |
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