A test of the space-for-time substitution hypothesis: North American bird responses to forest loss over space do not predict their responses over time

by

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfillment of the requirements of the degree of

Master of Science

in

Biology

Carleton University

Ottawa, Ontario

Abstract

The practice of space-for-time substitution in landscape ecology has provided vital insights for conservation policy, but whether these insights are reliable remains inconclusive. Here, my objective was to test space-for-time substitution using data from the North American Breeding Bird Survey (BBS) and Global Forest Change (GFC) to compare the effects of landscape-level forest cover on bird community metrics over time and space across 31 space-time comparisons in the United States and Canada. Temporal and spatial effects of forest cover on mean bird species richness and mean bird abundance were weakly correlated across the 31 comparisons for both forest and open-habitat species. Bird-forest cover relationships measured over time were more variable and inconsistent than those observed in space. Overall, my study results do not support the use of space-for-time substitution when studying North American birds.

Acknowledgements

I would first like to thank my co-supervisors Lenore Fahrig and Scott Wilson for their mentorship and guidance. Thank you also to Greg Mitchell and Gabriel Blouin-Demers for their helpful comments on developing versions of this project during the committee meetings. Additionally, I would like to extend my gratitude to Adam Smith for his help with learning how to build and run statistical models, the Bayesian way.

A big thank you goes out to all of the dedicated staff and volunteers of the North American Breeding Bird Survey (BBS). Likewise, thank you to the researchers at University of Maryland for producing Global Forest Change dataset. Without their shared knowledge, projects like mine would not be possible.

Last but not least, I would like to thank my dear friends and family, who offered shoulders to lean on, listening ears, and unconditional love and support.

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1. Introduction

Using long time series to study the causes of wildlife population change is frequently encouraged as a "gold standard" (Kratz et al. 2003) but is often not possible because time series data are lacking for most taxa (Strayer et al. 1988; McGarigal & Cushman 2002). This is because they are effort- and time-intensive to collect, costly, and complicated by land ownership, especially at the broad spatial scales most relevant for assessing population change (McGarigal & Cushman 2002). As a result, ecologists have used a so-called "space-for-time substitution" approach by studying wildlife responses along spatial gradients to predict how they would change along similar temporal gradients (Pickett 1989; De Palma et al. 2018). Space-for-time substitution remains a popular strategy despite a persisting lack of evidence that it produces reliable predictions.

In its early days, space-for-time substitution was used in chronosequence studies of vegetation succession and soil development (Cowles 1899; Pickett 1989) and is still commonly used today in those contexts (Walker et al. 2010; Miao et al. 2018). In recent decades, space-for-time substitution has been used to provide improved guidance for conservation decisions and land management. As one application, studies along altitudinal, CO_2, precipitation, and temperature gradients have been important for predicting how climate change affects biodiversity (Schlesinger 1990; Moore et al. 1999; Lester et al. 2014; Rustad 2008; Lemoine et al. 2007; Cushman & McGarigal 2003; De Palma et al. 2018). Other studies using space-for-time substitutions predict species responses to land cover change using comparisons across spatial gradients between disturbed and undisturbed sites (De Palma et al. 2018). Space-for-time substitution has also been used to predict the response of native communities to invasion by non-native species by comparing sites where invasive species are present vs. absent (Sax et al. 2005; Hejda et al. 2009).

Landscape ecology frequently assumes space-for-time substitution for questions relevant to conservation decisions (Fahrig 2003, Wardle et al. 1997; Marchand & Litvaitis 2004; Pardini et al. 2005; Sodhi et al. 2010; Frey-Ehrenbold et al. 2013). For example, Frey-Ehrenbold et al. (2013) suggest that measures to increase landscape connectivity could promote bat diversity, based on their comparisons across landscapes in Switzerland. Fahrig et al. (2015) and Martin et al. (2020) suggest that policies aimed at reducing crop field sizes would increase biodiversity, based on comparisons across agricultural landscapes in Canada. Galán-Acedo et al. (2019) state that forest restoration is needed to ensure persistence of primates, from their review of studies comparing primate abundance and occurrence across landscapes with different forest amounts. Such recommendations assume that patterns across space provide valid information for predicting what would happen over time under a given policy change.

Despite its application to inform conservation and land management policies, assuming that spatial patterns can predict temporal trends may be problematic. An inherent assumption when using space-for-time substitution is that the landscapes studied across space share identical histories and represent different stages of the temporal process being investigated (Pickett 1989; Johnson & Miyanishi 2008). However, different ecological mechanisms acting over time can produce similar patterns in space (Damgaard 2019). For instance, because each landscape arrives at its observed state in a given year from potentially different ecological processes other than the one being studied, a resulting spatial relationship might not be a reliable measure of the dynamics observed at a landscape that changes over time along a single trajectory. Critically, in spatial analysis scenarios, we often lack the historical data at our chosen landscapes to verify this assumption.

Birds are an excellent case study for testing the space-for-time substitution because, unlike most taxa, we have both extensive temporal and spatial data on birds. This wealth of data derives from citizen science databases such as the Christmas Bird Count (CBC) (National Audubon Society 2020), eBird (Sullivan et al. 2014), and the British Breeding Bird Survey (Harris et al. 2021). The North American Breeding Bird Survey (BBS), conducted since the 1970s, is probably the longest-running continent-scale citizen science database. The BBS, combined with advances in our ability to remotely-sense land cover change over time, provides an opportunity to the test space-for-time substitution over a broad spatial extent with a sufficiently-long time series.

Spatial analyses demonstrate that conversion of forest to farmland is a threat to forest birds and a benefit to open-habitat birds (Fischer et al. 2011; Mahood et al. 2012; Wilson et al. 2017; Endenburg et al. 2019). Variation in forest cover across space is a strong, positive predictor of forest bird abundance and richness (Trzcinski et al. 1999; Villard et al. 1999; Bélisle et al. 2001; Fahrig 2003; Betts et al. 2007). This relationship suggests that a similar change in forest cover over time would cause similar change in forest bird abundance and richness over time. We also expect that such a change in forest cover would cause the opposite change in open-habitat birds, which depend on landscapes dominated by crops, grasses, and pastures (Wright et al. 2012). While this type of space-for-time prediction is common in ecology, we lack evidence that wildlife community responses to forest change over time can be reliably predicted from community responses to similar differences in forest amount over space.

My objective was to test the space-for-time substitution assumption using the responses of North American forest-breeding and open-habitat-breeding birds to forest cover. If responses over time can be predicted by responses over space, then bird richness and abundance should respond to variation in forest cover similarly over time and space. Specifically, the slopes of the bird-forest cover relationships over time and space in the same region should be equal to each other.

2. Methods

2.1 Overview

I compared temporal and spatial bird responses to forest cover for 31 space-time comparisons. Each comparison contained one "temporal" site and multiple nearby (within 300 km) "spatial" sites. At the temporal site, I obtained data on birds and forest cover from 2000 to 2019. The spatial sites associated with that temporal site were sites that collectively represented a gradient in forest cover in the year 2019 that matched the gradient in forest cover that occurred at the temporal site before this. In other words, I asked whether a relationship across spatial sites between bird richness and abundance and forest cover in 2019 accurately predicted the actual change over time in bird richness and abundance over the same gradient in forest cover during the previous 19 years. In this way, my study mimicked 31 hypothetical field studies, each of which would have measured effects on bird richness and abundance of forest cover across space, and used the resulting relationship to infer changes in bird richness and abundance in response to an equivalent change in forest cover over time.

2.2. Bird Surveys

The BBS is a long-running bird monitoring program (1966 – present) consisting of over 4,000 annual volunteer-driven, roadside, count-based surveys (Environment Canada 2021). These standardized surveys are conducted in Canada, the US, and northern Mexico during peak breeding season between late May and early July (Sauer et al. 2013). Each 39.5-km-long route contains 50 stops spaced approximately 800 m apart along the road. At each stop, volunteers spend 3 minutes counting all individuals, identified to species, that are heard or seen within 400 m of the stop (Sauer et al. 2013). The BBS is cooperatively-run by the U.S. Geographic Survey's (USGS) Patuxent Wildlife Research Center (PWRC), Environment Canada's Canadian Wildlife Service (CWS), and Mexico's National Commission for the Knowledge and Use of Biodiversity (CONABIO). For my analysis, I only considered routes from Canada and continental U.S. because the survey has not been running long enough in Mexico to analyze long-term effects of changing forest cover (USGS & CONABIO 2021).

I obtained an up-to-date Canadian BBS route geodatabase with stop-level location information from the CWS's BBS administration team (personal communication 2020-02-03). A similar geodatabase was not available from the USGS and was instead obtained from a publicly-available online source (Patuxent Wildlife Research Center 1999). This US dataset contained geospatial data for whole routes but lacked individual stop locations. I estimated stop locations for the US routes by placing points 800 m apart along the length of the route using R 4.0.3 (R Core Team 2020) and ArcMap 10.8. I removed any routes where estimating stop locations would be difficult due to irregularlybranching roads, incomplete roads, or digitized routes with inaccurate BBS start point coordinates.

My sites consisted of bird occurrence data from the first 11 stops of each BBS route. I then created oblong landscapes surrounding each of the road segments. These extended 1 km from the road on either side, making each landscape approximately 8-km long to encompass the 11 stops, and covering an area of approximately 18-km^2. The 1-km distance was selected as the distance likely to encompass landscape features (here, forest cover) that might influence the individuals detected locally at each stop in the site (Wilson et al. 2017; Dornak et al. 2020). I used only the first 11 stops of the BBS routes based on Endenburg et al. (2019), and because using landscapes with smaller total area would increase the likelihood of finding sites that experienced enough percent forest cover change over time to evaluate a relationship over, which was required for the temporal site selection.

2.3 Forest Cover

I obtained forest cover information for 2000 to 2019 from the University of Maryland's Global Forest Change (GFC) dataset (v1.7; Hansen et al. 2013). This dataset consisted of three 30-m resolution raster layers. The first raster layer summarized global tree cover extent in 2000, where a given pixel's value reflected the percent canopy closure of the tree stands falling within the encompassed 900-m^2 area. The second raster layer contained annual tree cover loss information, where pixel classifications from 1 to 19 corresponded to the year (from 2001 to 2019) in which a given pixel experienced complete tree stand removal (Hansen et al. 2013). Lastly, the tree cover gain raster layer summarized pixels in which tree cover reached at least a 50% crown cover density in

2012 where previously there was none in 2000 (Hansen et al. 2013). Thus, tree cover gain information is only available for a single year, 2012, as a summary of all pixels that experienced tree cover gain some time within the 2000 to 2012 period. Using the R package *gfcanalysis* (v1.6.0; Cooper & Zvoleff 2020), I processed all three raster layers such that pixels containing tree stands with ≥ 50% canopy closure in 2000 were considered forest and any pixels < 50% canopy closure were considered open-habitat matrix. The transition from open habitat to forest is frequently defined by, or around, a threshold of 50% canopy closure (Rushing et al. 2016, Ocampo-Peñuela et al. 2016, Taylor & Stutchbury 2016; Hanberry & Thompson 2019).

I calculated forest cover from 2001 to 2019 at each site by extracting the number of forested pixels that were lost in each year and iteratively subtracting them from the number of forested pixels in the year before, starting with the layer of forest cover in 2000. In 2012, I added the number of pixels gained within the 2000 to 2012 period before subtracting lost pixels for that year. I calculated percent forest cover as the proportion of forested pixels in the landscape of each site-year combination. In addition, I calculated percent forest cover within 100 m of each stop of a given site-year to account for the effect of the adjacent habitat on forest or open-habitat bird detection. Using a buffer of 100 m ensured I was focusing on the immediate local surroundings of each stop, obtaining a more accurate representation of whether it was a survey point count that was truly located within either forested or open habitat. Within a site, I designated stops as being forested (≥ 60% forest cover within 100 m) or open (≤ 40% forest cover within 100 m). A stop's categorization as forested or open then determined whether the survey data collected at that stop contributed to the calculation of overall site-level response metrics of either forest or open-habitat birds, respectively (see Methods section 2.5). This was done so that both forest and open-habitat bird responses to forest cover change were being analyzed using data collected at survey points located adjacent to or within their preferred habitat.

2.4 Site Selection

To create multiple space-time comparisons, I carried out site selection in two distinct parts. First, I found sites that had sufficient forest cover and bird occurrence data spanning 2000 to 2019; these were potential temporal sites. I needed one temporal site for each evaluation of the space-for-time substitution. Second, for each temporal site, I selected a set of nearby spatial sites with forest and bird data available in the year 2019. The spatial sites associated with a given temporal site had to cover the same range in forest cover over space as the range in forest cover over time at the temporal site.

I selected potential temporal sites as those experiencing ≥ 20% change in forest cover from 2000 to 2019 and having at least 15 years of bird occurrence data over that time period. Applying a threshold of ≥ 20% forest cover change was important because analyzing how birds respond to forest cover change requires that forest cover actually changes. While the 20% change threshold is somewhat arbitrary, I chose this value as a trade-off between ensuring the forest cover gradients were large enough to detect species responses and maximizing the number of space-time comparisons I could make.

I matched spatial sites to each temporal site based on three criteria: a) the spatial sites had to fall within the same North American Level I Ecoregion (U.S. Environmental Protection Agency 2020) as the matching temporal site; b) the spatial sites had to be within 300 km of the matching temporal site; and c) the range of forest cover surrounding the spatial sites (in 2019) had to match the range of forest cover in the years 2000 to 2019 at the matching temporal site (± 5%). Using Level I Ecoregions and a distance criterion of 300 km ensured similar species pools among the spatial sites for a given space-time comparison. In particular, 300 km was chosen to ensure at least 15 spatial sites could be found to inform each comparison's spatial relationship, while also acting as the maximum distance before communities across landscapes would become too dissimilar to compare (Endenburg et al. 2019). In most comparisons, the number of spatial sites exceeded the number of years in the temporal site. To explore the role this might have played in the results of the space-time comparisons, I conducted each space-time comparison twice: once including all available spatial sites, and again including the number of spatial sites reduced to match the number of years in the corresponding temporal site. For the latter, I selected the spatial sites whose forest cover values most closely matched the forest cover values across years at the matching temporal site.

The final set of space-time comparisons fell within two Level I Ecoregions: 30 in the Eastern Temperate Forests of the eastern and southeastern US, and 1 in the Marine West Coastal Forests on Vancouver Island, Canada. The proximity between most eligible temporal sites meant that the spatial sites selected for each space-time comparison often overlapped (Figure 2). This means that the same spatial site could be included in more than one space-time comparison (Figure 2). However, no two comparisons had an identical set of spatial sites.

2.5 Data Analysis

My analysis focused on two bird guilds: species that breed in forests and species that breed in open grasslands (so-called "forest" or "open-habitat" birds; see Appendix

Table 1 for habitat designations). I summarized communities of forest and open-habitat birds at a given site using two metrics: mean species richness and mean abundance. Species richness at a stop was calculated as the total number of unique forest (or open-habitat) species present. Mean species richness was then the average number of forest (or open-habitat) species per forested (or open) stop. In other words, mean forest species richness was calculated only over the forested stops within the site and mean open-habitat species richness was calculated only over the open-habitat stops within the site. Bird abundance at a stop was the total number of forest (or open-habitat) individuals recorded, and mean abundance for a site was the average forest (or open-habitat) individuals per forested (or open) stop.

In all of the models, forest cover refers to the percent of forest in the landscape surrounding all 11 stops at a site (see above). The modelling was conducted in two stages. In the first stage, for each of the 31 space-time comparisons I estimated slopes relating bird responses to forest cover at (i) the temporal site over time ("temporal slopes"), and (ii) across the spatial sites ("spatial slopes"). There were four temporal slopes estimated per temporal site, one for each of mean species richness and mean abundance of forest species, and one for each of mean species richness and mean abundance of open-habitat species. The same four spatial slopes were estimated across the spatial sites associated with each temporal site. In addition, the set of four spatial slopes were estimated twice more, once using all of the spatial sites associated with a temporal site, and once using a subset of spatial sites that were selected to match the number of years of bird sampling at the associated temporal site (see Methods section 2.4 above). This resulted in eight dataset scenarios. Note that for each scenario, both temporal and spatial slopes were actually fit using a single model (see below). In the second stage, for each of these eight scenarios I then modelled the temporal slopes as a function of the spatial slopes across the 31 space-time comparisons. If the spatial relationships between birds and forest cover can predict the effect on birds of the same change in forest cover over time, then the slopes of these regressions should be 1.

I fit each of the eight models for estimating the temporal and spatial slopes using a Bayesian general linear model. Models were compiled and run with Stan's Hamiltonian Monte Carlo samplers using the R wrapper packages *cmdstanR* and *rstan* (Stan Development Team 2020). The models consisted of an intercept and slope parameter that varied by slope type (spatial or temporal) and by space-time comparison. Importantly, the model did not share or pool information across space-time comparisons for any parameter estimates. Intercepts and slopes were independently estimated within their grouping levels (space or time for each individual space-time comparison) and were not shrunk toward any grouping-level mean.

A known source of variation when analysing BBS data is the influence of different volunteers, or observer effects, on bird counts (Sauer et al. 1994). In the BBS, a single observer often surveys the same route for multiple years but most observers do not survey multiple routes. This means there are likely to be more different observers across spatial sites than over time for a temporal site (Sauer et al. 1994). It is also known that first-time observers tend to underestimate bird occurrences compared to their second or later surveys (Kendall et al. 1996). Thus, I controlled for observer effects and first-time observer effects by including both as covariates. As a final covariate, I also included the number of forested (or open-habitat) stops over which mean richness and abundance were calculated.

The final models for the slopes were structured as follows, where intercept (α) and slope (β) parameters were grouped by space-time comparison number (from 1 to 31) and slope type (temporal = 1, spatial = 2):

$$bird\ response \sim \alpha_{comparison\ \#,\ \ slope\ type} + \beta_{comparison\ \#,\ \ slope\ type} * percent\ forest \\ + observer_{observer\ \#} + first\ observer_{observation\ rank} + stops_{no.\ stops}$$

where $observer_{observer\ \#}$ measures the relative effect of each observer (from 1 to 240 observers) on bird richness or abundance, $first\ observer_{observation\ rank}$ measures the relative effect of observations being in an observer's first survey or not, and $stops_{no.\ stops}$ measures the relative effect of how many forested (or open) survey points the bird response was measured over (from 1 to 11 stops) for a given site-year observation.

I assessed the models for reasonable priors and posterior convergence using key diagnostic methods. I used weakly informative priors (i.e., ~ Normal(0, 1) and ~ Student-t(4, 0, 1)) that I established using prior predictive checks (Gabry et al. 2019). I ran each model for 2,000 iterations and 4 chains (for a total of 8,000 iterations). I assessed model convergence and fit using traceplots, the Gelman-Reuben statistic (*R-hat*; Gelman & Reuben 1992), the number of effective samples (N_{eff}), and posterior predictive checks.

I then evaluated the space-for-time substitution in two ways for each of the eight scenarios. First, I modelled temporal slopes as a function of spatial slopes across the 31 space-time comparisons using a series of simple linear regressions. To preserve the model's uncertainty around the temporal and spatial slope estimates, I repeated the regression 8,000 times for each of 8,000 sets of parameter iterations and calculated the mean predicted relationship with a 95% confidence interval. Second, I calculated the difference between temporal slopes and spatial slopes across all iterations for each space-time comparison to quantify how unequal the temporal and spatial slopes could be within the same space-time comparison.

3. Results

Overall, the 31 space-time comparisons included 118 forest species and 38 open-habitat species. For a given site, mean forest bird species richness ranged from 0 species per forested stop to 15 species per stop, with an average of 4.48. Mean open-habitat bird species richness ranged from 0 to 3.17 species per open-habitat stop, with an average of 0.59. Mean forest bird abundance for a site varied between 0 and 22 individuals per forested stop, with an average of 5.85. Mean open-habitat abundances spanned a larger range, from 0 to 27.14 individuals per open-habitat stop, but with a much lower average of 1.28.

All 31 temporal sites experienced net forest loss over the 19 years, from 20% (the minimum based on my site selection criteria), to largest forest loss of 49.2% loss (from 82.7% forest in 2000 to 33.5% forest in 2019). In some cases, temporal sites lost forest in small bursts every few years, while others experienced relatively continuous annual declines over the 19-year period. Only two sites experienced most of the forest loss in the span of only one or two years within the time period.

In general, results suggest that observed bird responses to forest cover over time do not align with the observed responses to forest cover over space. Notably, not only were temporal and spatial slopes typically uncorrelated and/or unequal (Table 1;

Appendix Figures A and B), but they could predict opposite directions of forest cover effects on birds in the same space-time comparison (i.e., a negative effect of forest cover over time and a positive effect of forest cover in space)). Out of the 8 data scenarios analyzed, 6 showed low – or even negative – correlations between the 31 matched temporal and spatial slopes measuring forest cover responses for forest and open-habitat birds (Figures 3, 4, and Table 1). The exception was for the scenarios of open-habitat bird richness and abundance when all spatial sites were included (time-versus-space slope = 0.610, 95% P.I. [-0.246, 1.912] and 1.251, 95% P.I. [0.121, 2.744], respectively; see Figures 3, 4, and Table 1). These showed the strongest congruence in forest cover effects between time and space although correlations were low (Pearson's r = 0.286 and 0.390, respectively; see Table 1). Interestingly, for both forest and open-habitat birds, when more spatial sites were considered in a comparison's spatial gradient relative to the number of years considered in the temporal gradient, the relationship between time and space effects became stronger (Table 1).

Across the 31 comparisons and 7 out of 8 scenarios, spatial slopes were consistently positive for forest birds and consistently negative for open-habitat birds, as expected (see x-axis of Figures 2 and 3). In contrast, the relationships between forest cover over time and forest bird richness or abundance over time were not as consistently positive (see y-axis of Figures 2 and 3; Appendix Figures and Tables C, D, G, H). Likewise, the relationships between forest cover over time and open-habitat bird richness or abundance over time were not consistently negative (see Appendix Figures and Tables E, F, I, J). Interestingly, even temporal sites with very similar forest cover gradients sometimes experienced opposite temporal trends in bird richness or abundance (e.g., compare Regions 28 and 31 in Appendix Figure C).

4. Discussion

I did not find support for the space-for-time substitution for North American birds. Specifically, I found that slopes measuring the effects of forest cover on bird richness and abundance over time were not consistently equal nor even positively correlated to spatial slopes across multiple comparisons. This mismatch between trends in time and space suggests that studies of bird responses differences across landscapes in forest cover are not a solid basis for making predictions about how birds would respond to a loss or gain in forest cover over time.

My results are consistent with the findings of other studies that attempt to directly compare time and space effects in birds. An early study by Flather & Sauer (1999) used data from the BBS to compare time and space effects of landscape structure on Neotropical migratory birds. They found that, over time, migrant birds were often negatively associated with increased vegetation cover, in contradiction to the consistently positive associations observed in space (Flather & Sauer 1999). At the time, the authors were limited to a cross-sectional dataset of land cover snapshots in 1966 and 1993 only and lacked the ability to annually track land cover change (Flather & Sauer 1999). More recently, La Sorte and colleagues used BBS data to compare temporal trends in North American bird responses to climate change with a space-for-time substitution, finding that the predicted responses of bird body mass and occupancy to changing temperature measured in space were not able to sufficiently explain actual observed trends in body mass and occupancy over time (La Sorte et al. 2009). This incongruence between time and space was also shown by Bonthoux et al. (2013). They sampled an agricultural landscape in southwest France in 1982 and 2007. They found that species richness and two community specialisation indices were associated with landscape composition less consistently over time than in space (Bonthoux et al. 2013). Finally, a recent study by Gaüzère & Devictor (2021) in France revealed that the effect of local human activities on bird distributions in space was not a strong predictor of how bird distributions changed in response to human activities over time. They even found that bird abundance patterns in time and space became more different from each other with greater anthropogenic disturbance.

In this study, the mismatch between temporal slopes and spatial slopes appears to be tied to greater inconsistency in bird responses to forest cover over time than over space, mirroring the results of Bonthoux et al. 2013. My results showed that, across the 31 space-time comparisons, spatial slopes aligned more consistently than temporal slopes to the expected relationships between bird richness or abundance and forest cover change. Specifically, bird responses across space aligned well with the expectation that forest birds increase and open-habitat birds decrease, in both richness and abundance, as forest cover increases. In contrast, bird responses to forest change over time were often opposite to these expectations, with both negative and positive temporal slopes (Figures 2 and 3). In a conservation context, this indicates that how birds respond to changing forest cover amount across landscapes in space might produce overly optimistic predictions for how a certain increase in forest cover over time would be expected to result in an certain increase in forest birds and a certain decrease in open-habitat birds. Here, temporal relationships instead suggest that restoring forest cover in a landscape over time may not always have as strong of an effect on recovering species as was predicted by a spatial analysis.

I speculate that bird-forest cover relations over space are more consistent than they are over time because more variables influence birds over time than over space. The most obvious are weather variables. Within a given year (here 2019) the spatial sites in a particular space-time comparison likely experienced similar weather conditions. In contrast, at a given temporal site, weather will fluctuate over time. Changing weather patterns can both directly and indirectly impact bird populations on the breeding grounds, wintering grounds, and along the migratory routes (Sillett et al. 2000; Drake et al. 2014; Wilson et al. 2010; Wilson et al. 2018; Hill et al. 2019). These impacts may influence local abundance and diversity on the breeding grounds to a greater extent than forest cover alone. Acting directly, weather conditions along the migratory route – such as storms, high winds, or drought – can influence the number of individuals that settle on the breeding grounds in the spring (Drake et al. 2014; Wilson et al. 2018). Indirectly, climatic conditions can create variability in local availability of fruits, seeds, and insects, which can affect bird survival rates (Both et al. 2010; Sillett et al. 2000; Hill et al. 2019). In addition, seasonal disease outbreaks would add to inter-annual variation in bird abundance and diversity (Hochachka & Dhondt 2000; Hernandez et al. 2012), further decoupling the relationship between birds and forest cover.

The fact that many of the species included in my analysis are seasonal and directional migrants could explain the greater inconsistency in the effects of breeding ground forest cover over time than in space. Here, 80 out of the 118 forest species and 17 out of the 36 open-habitat species were migratory. Migratory birds have complex annual cycles, such that their populations are limited by a host of factors operating simultaneously on the breeding grounds, migratory route, and on the non-breeding grounds, with evidence pointing toward migration (Sillett & Holmes 2002; Klaassen 2014; Lok et al. 2015; Hewson et al. 2016) and non-breeding ground threats (Taylor & Stutchbury 2016; La Sorte et al. 2017; Dokter et al. 2018) being the most relevant. Changes not only in climate, but in forest and matrix composition and configuration at critical stopover sites or overwintering grounds over time, may be considerable drivers of population change that cannot be accounted for by a spatial analysis focusing solely on breeding ground forest cover amounts in a single year.

Unmeasured lag effects might further decouple the relationship in time between birds and first cover. Observed annual bird richness and abundance may be more strongly related to past forest cover at a site than to the forest cover present in that year. Indeed, a site's past landscape has been shown to be a powerful predictor of present-day species assemblages in birds and other taxa, in some cases with a time lag of up to 25 years (Wiens & Rotenberry 1985; Brooks et al. 1999; Foster et al. 2003; Ernoult et al. 2005; Saether et al. 2005). In my study, time-lagged bird responses are a plausible explanation for some of the negative effects of increasing forest cover on forest birds and positive effects of increasing forest cover on open-habitat birds that were observed at some temporal sites. This would be the case if, at these temporal sites, forest and open-habitat birds were responding to past forest cover sequences that had occurred prior to my study period. For instance, if forest cover increased in the years leading up to my study and then only began to markedly decrease after 2000, as observed here, the trend that forest birds seem to be increasing with forest loss from 2000 to 2019 might be a lagged response of 10 years or more to forest gain that had occurred previously.

Features of the dataset itself could be relevant for explaining inconsistent results in time. Most notably, the Global Forest Change (GFC) dataset is limited in its ability to track and quantify forest cover gain over time. Specifically, it only considers a 30-m pixel to have experienced tree cover gain if it transitioned from being completely open habitat in 2000 to having tree cover with at least 50% crown cover density in 2012 (Hansen et al. 2013). Thus, my estimates of annual forest cover at a temporal site may be underestimated, which could explain why bird-forest cover relationships over time did not align consistently with my expectations. However, because my annual estimates of forest cover were calculated iteratively from year to year, the forest cover estimates in 2019 for each spatial site are also likely underestimated. Despite this, I still observed the expected bird-forest cover relationships more consistently in space for both forest and open-habitat birds across the majority of space-time comparisons.

The fact that many of the spatial sites were used in multiple space-time comparisons does not explain the observed higher consistency with expected bird-forest relationships in space than in time. Because of this overlap we expect sets of similar spatial slopes. However, we would still expect the bird-forest cover relationships observed in space to be reflected in the temporal trajectories of nearby sites if the space-for-time substitution is valid (De Palma et al. 2018). Additionally, the overlap cannot explain why independent temporal sites show opposite effects of forest cover on birds (e.g., compare Region 28 to 31 in Appendix Figure C), or why effects in space are more consistent with the expected direction of forest cover effects for forest and open-habitat species.

The 1:1 assumption of space-for-time substitution is not unfamiliar to criticism in broader contexts. Indeed, other studies have also adverted caution in using space-for-time substitution when studying landscape processes, building climate forecasting models, sampling for occupancy, or evaluating vegetation succession dynamics (Adler & Levine 2007; Isaac et al. 2011; Jochner et al. 2013; Mimet et al. 2016; França et al. 2016; Oedekoven et al. 2017; De Lombaerde et al. 2018). However, some studies have found moderate support for space-for-time substitutions (Charbonnel et al. 2014; Guittar et al. 2016; Miao et al. 2018; Klesse et al. 2020), and some even find that it works well (Sparling et al. 2003; Walker et al. 2010; Banet & Trexler 2013, Hammond & Kolasa 2014; Blois et al. 2013; Rolo et al. 2016; Wogan & Wang 2018; Srivathsa et al. 2018). This inconsistency in support for space-for-time substitution over the past two decades suggests that the question is not simply "whether" space-for-time substitution is valid, but "where", "when", and in "what" systems it may be most reliable.

My study results, in combination with others, can provide insights into where space-for-time substitution might work best. Recent work suggests that space-for-time substitution may favour animals with high mobility and fast generation times (Banet & Trexler 2013), because they can respond quickly to environmental change (Damgaard 2019). In particular, being highly mobile could allow animals to track local habitat changes as they occur throughout the year. However, animals that are migratory and return to the same location to breed every year, as in Neotropical birds, may have fewer opportunities to respond to unfavourable habitat changes that occurred during their absence promptly enough to still breed on time, especially if they decide on nesting sites based on past reproductive successes and/or proximity to their birth site (Hoover 2003; Harrison et al. 2010). From this, I speculate that the space-for-time substitution would likely also fail for other migratory animals, such as butterflies. Temporal variation in migratory butterfly abundance could be equal to or greater than in birds because annual butterfly distribution and seasonal migration is closely linked to climate conditions, which can be considerably variable over time (Isaac et al. 2011; Chowdhury et al. 2021). Taxa- or even species-specific analyses exploring the role of migratory behaviour in space-for-time substitution's effectiveness could be an interesting avenue for further exploration.

In conclusion, space-for-time substitution does not work consistently for predicting bird responses to changing forest cover in North America. As such, using patterns we observe in space to inform conservation policies requires caution and a need to better understand when space-for-time substitution is reliable. Space-for-time substitution, as applied through spatial analyses, remain a useful tool for investigating the impact of environmental variables on wildlife while controlling for temporal variation. However, my results highlight how spatial analyses may oversimplify the complex temporal processes responsible for long-term population change. Further, spatial analyses could be overly optimistic in predicting how changing breeding habitat actually affects birds relative to other important environmental variables operating over time. My results therefore underscore the importance of remaining critical of the assumptions associated with predicting wildlife changes over time based on observed spatial patterns.

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Tables

Table 1. Mean regression coefficients (with associated 95% percentile intervals (PI)) and correlation coefficients (Pearson's r) measuring the congruency between a) estimated forest and open-habitat bird-forest cover slopes over time at a temporal site from 2000 to 2019 ("temporal slope") and b) estimated forest and open-habitat bird-forest cover slopes in space across a set of neighbouring spatial sites in 2019 ("spatial slope"). Spatial slopes were estimated twice: once where the number of spatial sites informing the spatial slope matched with the number of years informing the corresponding temporal slope (scenario I) and again where the maximum number of eligible spatial sites was used to inform the spatial slope (scenario II).

Response Metric	Model	Average Temporal vs. Spatial Slope	95% PI	Pearson's r
Mean species richness	Forest (scenario I)	-0.259	[-0.835, 0.342]	-0.316
	Open-habitat (scenario I)	0.192	[-0.620, 1.009]	0.195
	Forest (scenario II)	0.170	[-0.520, 0.866]	0.105
	Open-habitat (scenario II)	0.610	[-0.246, 1.912]	0.286
Mean abundance	Forest (scenario I)	-0.445	[-0.981, 0.089]	-0.402
	Open-habitat (scenario I)	0.111	[-0.988, 1.169]	0.096
	Forest (scenario II)	-0.557	[-1.339, 0.179]	-0.250
	Open-habitat (scenario II)	1.251	[0.121, 2.744]	0.390

Figures

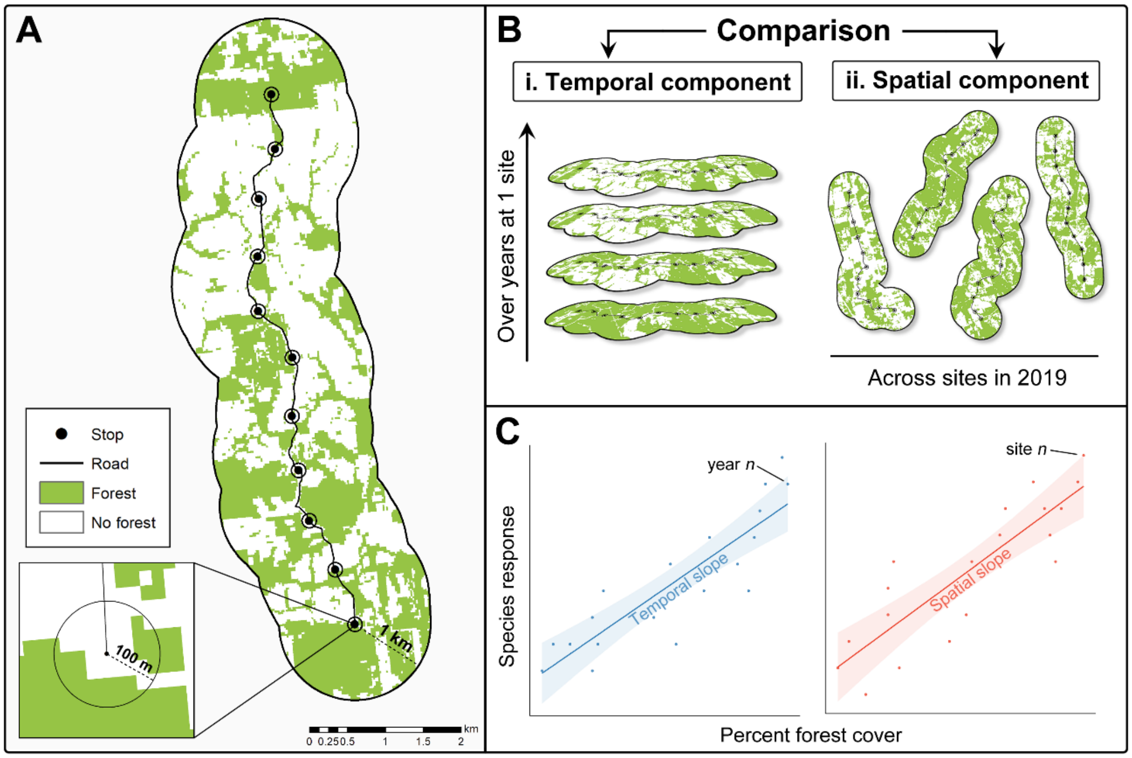


Figure 1. Visual description of the space-time comparison study design where A) a site consisted of the first 11 "stops" of a North American Breeding Bird Survey (BBS) route, along with the landscape within 1-km, within which forest cover was measured. Individual stops were characterized as forested (≥ 60% forest within 100 m) or not forested (≤ 40% forest within 100 m). B) Sites were organized into "space-time comparisons," consisting of a single "temporal site" with bird and forest information from 2000 to 2019, and multiple "spatial sites" covering the same 2019 forest gradient over space as the forest gradient over time at the associated temporal site. C) The relationship between bird species responses and percent forest cover was estimated as a slope over time at the temporal site and over space across the associated spatial sites.

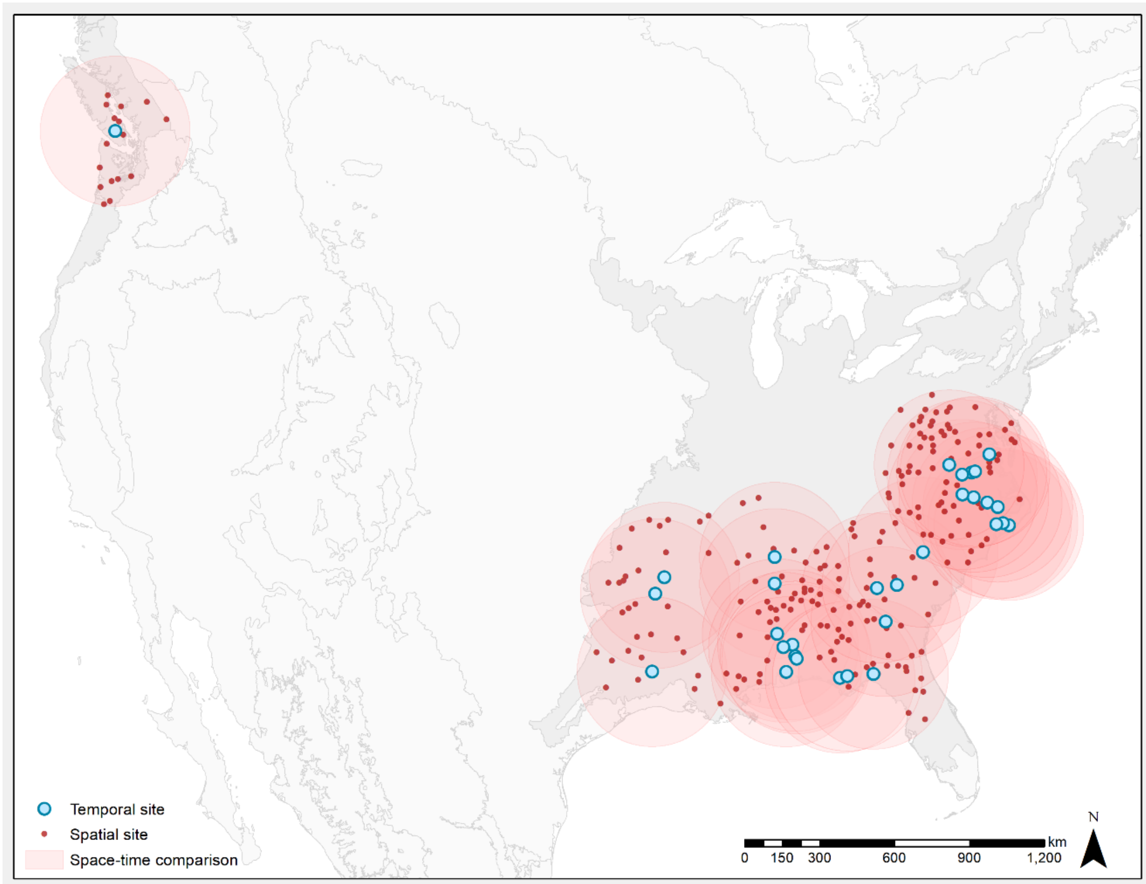


Figure 2. Locations of 31 space-time comparisons within the continental United States (U.S.) and Canada, each consisting of a single temporal site (gradient of forest cover over time) and a series of matched spatial sites (gradient of forest cover across space) located within a 300-km radius buffer of the temporal site. Comparison regions fell in two Level I Ecoregions: Marine West Coastal Forest (left-most dark grey area) and the Eastern Temperate Forests (right-most dark grey area).

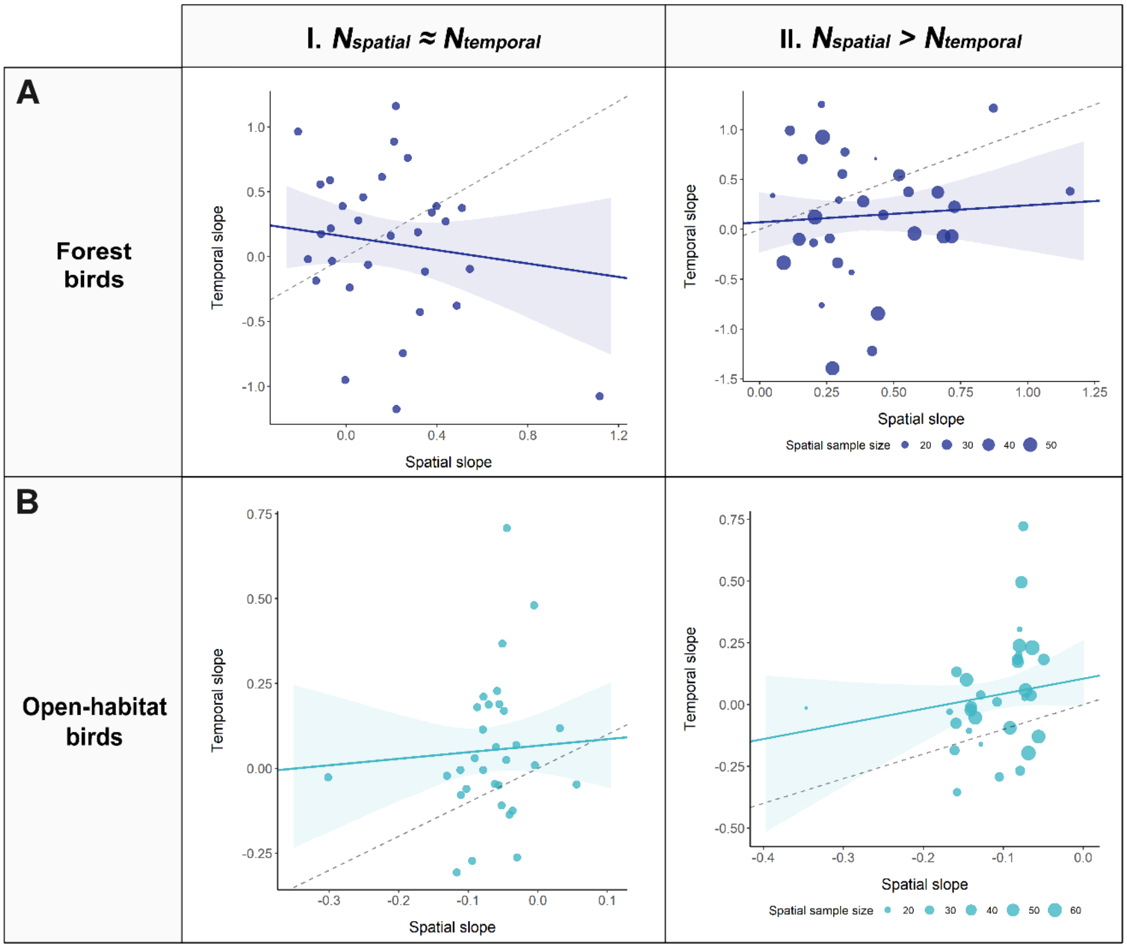


Figure 3. Relationships between estimated slopes measuring the effect of forest cover change on forest (A) and open-habitat (B) mean bird species richness over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope"). Each of the 31 space-time comparisons contains one temporal and one spatial slope measuring forest cover effects and corresponds to a single point in the figure. Spatial slopes were estimated twice: once where the number of spatial sites informing the spatial slope matched with the number of years informing the corresponding temporal slope (scenario I) and again where the maximum number of eligible spatial sites was used to inform the spatial slope (scenario II). Plotted regression lines represent the mean relationship obtained by summarizing over 12,000 linear regressions for each of 12,000 sets of Markov Chain Monte Carlo parameter iterations, with 95% percentile intervals shaded. The dotted line represents a 1:1 relationship ($\alpha = 0$, $\beta = 1$).

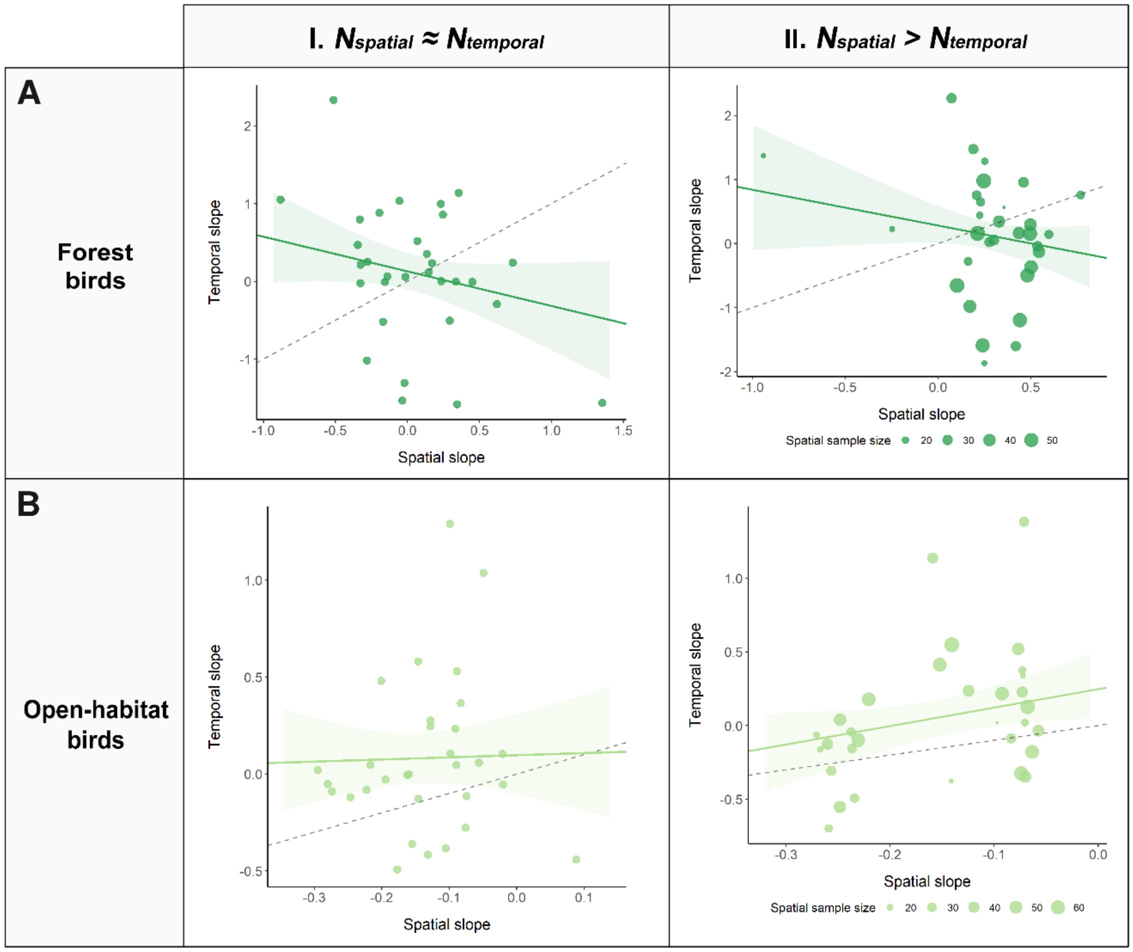


Figure 4. Correlation between estimated slopes measuring the effect of forest cover change on forest (A) and open-habitat (B) mean bird abundance over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope"). Each of the 31 space-time comparisons contains one temporal and one spatial slope measuring forest cover effects and corresponds to a single point in the figure. Spatial slopes were estimated twice: once where the number of spatial sites informing the spatial slope matched with the number of years informing the corresponding temporal slope (scenario I) and again where the maximum number of eligible spatial sites was used to inform the spatial slope (scenario II). Plotted regression lines represent the mean relationship obtained by summarizing over 12,000 linear regressions for each of 12,000 sets of Markov Chain Monte Carlo parameter iterations, with 95% percentile intervals shaded. The dotted line represents a 1:1 relationship ($\alpha = 0$, $\beta = 1$).

Appendices

Table A. Summary of 31 space-time comparisons selected for analysis. Space-time comparisons were centered on a modified BBS route that has experienced at least 20% forest cover change from 2000 to 2019 ("temporal site") and that has at least 15 years' worth of BBS data spanning the full 19-year time period. Each temporal site was matched to a series of neighbouring spatial sites in the same EPA Level I Ecoregion (Ecoregion 7 = Marine West Coast Forests, Ecoregion 8 = Eastern Temperate Forests; EPA 2021) that collectively covered a similar forest cover gradient in 2019 ("spatial sites"). All sites used in the analysis were composed of the first 11 stops (approximately 8 km) of the original BBS route.

Space-time Comparison	BBS Route	Level I Ecoregion	Min % forest cover	Max % forest cover	# Years	# Spatial sites
1	2021	8	0.417	0.774	19	39
2	2036	8	0.586	0.810	16	25
3	2038	8	0.389	0.726	19	42
4	2045	8	0.449	0.720	20	52
5	2066	8	0.371	0.668	19	40
6	2214	8	0.599	0.904	19	20
7	2218	8	0.455	0.757	19	31
8	7013	8	0.497	0.733	18	15
9	7111	8	0.391	0.882	20	31
10	11402	7	0.482	0.714	20	16
11	25005	8	0.395	0.688	16	25
12	25010	8	0.514	0.864	20	28
13	25108	8	0.393	0.594	15	24
14	27031	8	0.371	0.636	20	49
15	27032	8	0.439	0.668	15	39
16	27050	8	0.285	0.689	20	50
17	42122	8	0.449	0.814	18	17
18	63002	8	0.458	0.716	20	17
19	63010	8	0.345	0.564	20	30
20	63024	8	0.521	0.747	20	30
21	63108	8	0.474	0.804	20	20
22	63109	8	0.285	0.768	18	34

Space-time Comparison	BBS Route	Level I Ecoregion	Min % forest cover	Max % forest cover	# Years	# Spatial sites
23	63232	8	0.522	0.763	18	44
24	63311	8	0.335	0.827	20	29
25	80112	8	0.546	0.807	16	24
26	82015	8	0.449	0.708	17	51
27	88023	8	0.577	0.814	20	53
28	88025	8	0.501	0.768	17	55
29	88028	8	0.416	0.734	20	56
30	88049	8	0.486	0.707	16	50
31	88914	8	0.613	0.835	20	30

Table B. All species detected in the bird surveys used in this study. In our analyses we included only the 118 forest breeding species (F) and the 38 open-habitat breeding species (O). Other symbols are FE = forest- or shrub-edge breeders, W = wetland or shoreline breeders, N = nocturnal species. Species designations were based on information in the Birds of North America (Rodewald 2018).

Common Name	Scientific Name	Breeding Habitat
Acadian Flycatcher	*Empidonax virescens*	F
Acorn Woodpecker	*Melanerpes formicivorus*	F
Alder Flycatcher	*Empidonax alnorum*	FE
Allen's Hummingbird	*Selasphorus sasin*	O
American Avocet	*Recurvirostra americana*	W
American Bittern	*Botaurus lentiginosus*	W
American Black Duck	*Anas rubripes*	W
American Coot	*Fulica americana*	W
American Crow	*Corvus brachyrhynchos*	FE
American Dipper	*Cinclus mexicanus*	F
American Goldfinch	*Spinus tristis*	FE
American Kestrel	*Falco sparverius*	O
American Pipit	*Anthus rubescens*	O
American Redstart	*Setophaga ruticilla*	F
American Robin	*Turdus migratorius*	FE
American Three-toed Woodpecker	*Picoides dorsalis*	F
American White Pelican	*Pelecanus erythrorhynchos*	W
American Wigeon	*Mareca americana*	W
American Woodcock	*Scolopax minor*	F
Anhinga	*Anhinga anhinga*	W
Anna's Hummingbird	*Calypte anna*	FE
Arctic Tern	*Sterna paradisaea*	W
Ash-throated Flycatcher	*Myiarchus cinerascens*	FE
Bachman's Sparrow	*Peucaea aestivalis*	F
Bald Eagle	*Haliaeetus leucocephalus*	FE
Baltimore Oriole	*Icterus galbula*	F
Band-tailed Pigeon	*Patagioenas fasciata*	F
Bank Swallow	*Riparia riparia*	O
Barn Owl	*Tyto alba*	N

Common Name	Scientific Name	Breeding Habitat
Barn Swallow	*Hirundo rustica*	O
Barred Owl	*Strix varia*	N
Barrow's Goldeneye	*Bucephala islandica*	W
Bay-breasted Warbler	*Setophaga castanea*	F
Bell's Sparrow	*Artemisiospiza belli*	O
Belted Kingfisher	*Megaceryle alcyon*	W
Bewick's Wren	*Thryomanes bewickii*	F
Bicknell's Thrush	*Catharus bicknelli*	F
Black Phoebe	*Sayornis nigricans*	F
Black Swift	*Cypseloides niger*	F
Black Tern	*Chlidonias niger*	W
Black Vulture	*Coragyps atratus*	FE
Black-and-white Warbler	*Mniotilta varia*	F
Black-backed Woodpecker	*Picoides arcticus*	F
Black-bellied Whistling-Duck	*Dendrocygna autumnalis*	W
Black-billed Cuckoo	*Coccyzus erythropthalmus*	F
Black-billed Magpie	*Pica hudsonia*	O
Blackburnian Warbler	*Setophaga fusca*	F
Black-capped Chickadee	*Poecile atricapillus*	F
Black-chinned Hummingbird	*Archilochus alexandri*	F
Black-chinned Sparrow	*Spizella atrogularis*	O
Black-crowned Night-Heron	*Nycticorax nycticorax*	W
Black-headed Grosbeak	*Pheucticus melanocephalus*	F
Black-necked Stilt	*Himantopus mexicanus*	W
Blackpoll Warbler	*Setophaga striata*	F
Black-tailed Gnatcatcher	*Polioptila melanura*	O
Black-throated Blue Warbler	*Setophaga caerulescens*	F
Black-throated Gray Warbler	*Setophaga nigrescens*	F
Black-throated Green Warbler	*Setophaga virens*	F
Black-throated Sparrow	*Amphispiza bilineata*	O
Blue Grosbeak	*Passerina caerulea*	FE
Blue Jay	*Cyanocitta cristata*	F
Blue-gray Gnatcatcher	*Polioptila caerulea*	F
Blue-headed Vireo	*Vireo solitarius*	F
Blue-winged Teal	*Spatula discors*	W

Common Name	Scientific Name	Breeding Habitat
Blue-winged Warbler	*Vermivora cyanoptera*	O
Boat-tailed Grackle	*Quiscalus major*	O
Bobolink	*Dolichonyx oryzivorus*	O
Bohemian Waxwing	*Bombycilla garrulus*	F
Bonaparte's Gull	*Chroicocephalus philadelphia*	W
Boreal Chickadee	*Poecile hudsonicus*	F
Brewer's Blackbird	*Euphagus cyanocephalus*	O
Brewer's Sparrow	*Spizella breweri*	O
Broad-tailed Hummingbird	*Selasphorus platycercus*	F
Broad-winged Hawk	*Buteo platypterus*	F
Brown Creeper	*Certhia americana*	F
Brown Pelican	*Pelecanus occidentalis*	W
Brown Thrasher	*Toxostoma rufum*	FE
Brown-headed Cowbird	*Molothrus ater*	O
Brown-headed Nuthatch	*Sitta pusilla*	F
Bufflehead	*Bucephala albeola*	W
Bullock's Oriole	*Icterus bullockii*	F
Burrowing Owl	*Athene cunicularia*	O
Bushtit	*Psaltriparus minimus*	F
California Gull	*Larus californicus*	W
California Quail	*Callipepla californica*	O
California Scrub-Jay	*Aphelocoma californica*	FE
California Thrasher	*Toxostoma redivivum*	O
California Towhee	*Melozone crissalis*	O
Calliope Hummingbird	*Selasphorus calliope*	F
Canada Goose	*Branta canadensis*	W
Canada Jay	*Perisoreus canadensis*	F
Canada Warbler	*Cardellina canadensis*	F
Canyon Wren	*Catherpes mexicanus*	O
Cape May Warbler	*Setophaga tigrina*	F
Carolina Chickadee	*Poecile carolinensis*	F
Carolina Wren	*Thryothorus ludovicianus*	F
Caspian Tern	*Hydroprogne caspia*	W
Cassin's Finch	*Haemorhous cassinii*	F
Cassin's Kingbird	*Tyrannus vociferans*	F

Common Name	Scientific Name	Breeding Habitat
Cassin's Vireo	*Vireo cassinii*	F
Cattle Egret	*Bubulcus ibis*	W
Cave Swallow	*Petrochelidon fulva*	O
Cedar Waxwing	*Bombycilla cedrorum*	F
Cerulean Warbler	*Setophaga cerulea*	F
Chestnut-backed Chickadee	*Poecile rufescens*	F
Chestnut-sided Warbler	*Setophaga pensylvanica*	F
Chimney Swift	*Chaetura pelagica*	O
Chipping Sparrow	*Spizella passerina*	F
Chuck-will's-widow	*Antrostomus carolinensis*	N
Chukar	*Alectoris chukar*	O
Cinnamon Teal	*Spatula cyanoptera*	W
Clark's Nutcracker	*Nucifraga columbiana*	F
Clay-colored Sparrow	*Spizella pallida*	O
Cliff Swallow	*Petrochelidon pyrrhonota*	O
Common Gallinule	*Gallinula galeata*	W
Common Goldeneye	*Bucephala clangula*	W
Common Grackle	*Quiscalus quiscula*	F
Common Ground Dove	*Columbina passerina*	O
Common Loon	*Gavia immer*	W
Common Merganser	*Mergus merganser*	W
Common Murre	*Uria aalge*	W
Common Nighthawk	*Chordeiles minor*	N
Common Poorwill	*Phalaenoptilus nuttallii*	N
Common Raven	*Corvus corax*	FE
Common Tern	*Sterna hirundo*	W
Common Yellowthroat	*Geothlypis trichas*	O
Connecticut Warbler	*Oporornis agilis*	F
Cooper's Hawk	*Accipiter cooperii*	F
Cordilleran Flycatcher	*Empidonax occidentalis*	F
Costa's Hummingbird	*Calypte costae*	O
Dark-eyed Junco	*Junco hyemalis caniceps*	F
Dickcissel	*Junco hyemalis oreganus*	O
Double-crested Cormorant	*Junco hyemalis hyemalis*	W
Downy Woodpecker	*Junco hyemalis aikeni*	F

Common Name	Scientific Name	Breeding Habitat
Dusky Flycatcher	*Spiza americana*	F
Dusky Grouse	*Phalacrocorax auritus*	F
Eared Grebe	*Dryobates pubescens*	W
Eastern Bluebird	*Empidonax oberholseri*	FE
Eastern Kingbird	*Dendragapus obscurus*	FE
Eastern Meadowlark	*Podiceps nigricollis*	O
Eastern Phoebe	*Sialia sialis*	FE
Eastern Screech-Owl	*Tyrannus tyrannus*	N
Eastern Towhee	*Sturnella magna*	FE
Eastern Whip-poor-will	*Sayornis phoebe*	F
Eastern Wood-Pewee	*Megascops asio*	F
Eurasian Collared-Dove	*Pipilo erythrophthalmus*	O
European Starling	*Antrostomus vociferus*	O
Evening Grosbeak	*Contopus virens*	F
Field Sparrow	*Streptopelia decaocto*	O
Fish Crow	*Sturnus vulgaris*	FE
Forster's Tern	*Coccothraustes vespertinus*	W
Fox Sparrow	*Spizella pusilla*	F
Franklin's Gull	*Corvus ossifragus*	W
Gadwall	*Sterna forsteri*	W
Glaucous-winged Gull	*Passerella iliaca*	W
Golden Eagle	*Leucophaeus pipixcan*	O
Golden-crowned Kinglet	*Mareca strepera*	F
Golden-crowned Sparrow	*Larus glaucescens*	O
Golden-winged Warbler	*Aquila chrysaetos*	FE
Grace's Warbler	*Regulus satrapa*	F
Grasshopper Sparrow	*Zonotrichia atricapilla*	O
Gray Catbird	*Vermivora chrysoptera*	FE
Gray Flycatcher	*Setophaga graciae*	O
Gray Kingbird	*Ammodramus savannarum*	F
Gray-cheeked Thrush	*Dumetella carolinensis*	F
Gray-crowned Rosy-Finch	*Empidonax wrightii*	O
Great Black-backed Gull	*Tyrannus dominicensis*	W
Great Blue Heron	*Catharus minimus*	W
Great Crested Flycatcher	*Leucosticte tephrocotis*	F

Common Name	Scientific Name	Breeding Habitat
Great Egret	*Larus marinus*	W
Great Gray Owl	*Ardea herodias*	N
Great Horned Owl	*Myiarchus crinitus*	N
Greater Roadrunner	*Ardea alba*	O
Greater Yellowlegs	*Strix nebulosa*	W
Great-tailed Grackle	*Bubo virginianus*	FE
Green Heron	*Geococcyx californianus*	W
Green-tailed Towhee	*Tringa melanoleuca*	O
Green-winged Teal	*Quiscalus mexicanus*	W
Hairy Woodpecker	*Butorides virescens*	F
Hammond's Flycatcher	*Pipilo chlorurus*	F
Harlequin Duck	*Anas crecca*	W
Heermann's Gull	*Dryobates villosus*	W
Henslow's Sparrow	*Empidonax hammondii*	O
Hepatic Tanager	*Histrionicus histrionicus*	F
Hermit Thrush	*Larus heermanni*	F
Hermit Warbler	*Centronyx henslowii*	F
Herring Gull	*Piranga flava*	W
Hooded Merganser	*Catharus guttatus*	W
Hooded Oriole	*Setophaga occidentalis*	F
Hooded Warbler	*Larus argentatus*	F
Horned Lark	*Lophodytes cucullatus*	O
House Finch	*Icterus cucullatus*	FE
House Sparrow	*Setophaga citrina*	O
House Wren	*Eremophila alpestris*	FE
Hutton's Vireo	*Haemorhous mexicanus*	F
Inca Dove	*Passer domesticus*	O
Indigo Bunting	*Troglodytes aedon*	FE
Juniper Titmouse	*Vireo huttoni*	F
Kentucky Warbler	*Columbina inca*	F
Killdeer	*Passerina cyanea*	O
King Rail	*Baeolophus ridgwayi*	W
Ladder-backed Woodpecker	*Geothlypis formosa*	O
Lark Sparrow	*Charadrius vociferus*	O
Laughing Gull	*Rallus elegans*	W

Common Name	Scientific Name	Breeding Habitat
Lawrence's Goldfinch	*Dryobates scalaris*	O
Lazuli Bunting	*Chondestes grammacus*	F
Least Bittern	*Leucophaeus atricilla*	W
Least Flycatcher	*Spinus lawrencei*	F
Least Tern	*Passerina amoena*	W
LeConte's Sparrow	*Ixobrychus exilis*	O
Lesser Goldfinch	*Empidonax minimus*	O
Lesser Scaup	*Sternula antillarum*	W
Lesser Yellowlegs	*Ammospiza leconteii*	W
Lewis's Woodpecker	*Spinus psaltria*	F
Limpkin	*Aythya affinis*	W
Lincoln's Sparrow	*Tringa flavipes*	FE
Little Blue Heron	*Melanerpes lewis*	W
Loggerhead Shrike	*Aramus guarauna*	O
Long-eared Owl	*Melospiza lincolnii*	N
Louisiana Waterthrush	*Egretta caerulea*	F
Lucy's Warbler	*Lanius ludovicianus*	O
MacGillivray's Warbler	*Asio otus*	FE
Magnolia Warbler	*Parkesia motacilla*	F
Mallard	*Leiothlypis luciae*	W
Marsh Wren	*Geothlypis tolmiei*	O
Merlin	*Setophaga magnolia*	FE
Mexican Whip-poor-will	*Anas platyrhynchos*	F
Mississippi Kite	*Cistothorus palustris*	FE
Montezuma Quail	*Falco columbarius*	F
Mountain Bluebird	*Antrostomus arizonae*	FE
Mountain Chickadee	*Ictinia mississippiensis*	F
Mountain Quail	*Cyrtonyx montezumae*	O
Mourning Dove	*Sialia currucoides*	FE
Mourning Warbler	*Poecile gambeli*	FE
Nashville Warbler	*Oreortyx pictus*	F
Neotropic Cormorant	*Zenaida macroura*	W
Northern Bobwhite	*Geothlypis philadelphia*	F
Northern Cardinal	*Leiothlypis ruficapilla*	FE
Northern Flicker	*Phalacrocorax brasilianus*	F

Common Name	Scientific Name	Breeding Habitat
Northern Gannet	*Colinus virginianus*	W
Northern Goshawk	*Cardinalis cardinalis*	F
Northern Harrier	*Colaptes auratus cafer*	O
Northern Hawk Owl	*Colaptes auratus auratus*	F
Northern Mockingbird	*Morus bassanus*	FE
Northern Parula	*Accipiter gentilis*	F
Northern Pintail	*Circus hudsonius*	W
Northern Pygmy-Owl	*Surnia ulula*	F
Northern Rough-winged Swallow	*Mimus polyglottos*	O
Northern Saw-whet Owl	*Setophaga americana*	N
Northern Shoveler	*Anas acuta*	W
Northern Waterthrush	*Glaucidium gnoma*	F
Nuttall's Woodpecker	*Stelgidopteryx serripennis*	F
Oak Titmouse	*Aegolius acadicus*	F
Olive Warbler	*Spatula clypeata*	F
Olive-sided Flycatcher	*Parkesia noveboracensis*	F
Orange-crowned Warbler	*Dryobates nuttallii*	F
Orchard Oriole	*Baeolophus inornatus*	F
Osprey	*Peucedramus taeniatus*	FE
Ovenbird	*Contopus cooperi*	F
Pacific Wren	*Leiothlypis celata*	F
Pacific-slope Flycatcher	*Icterus spurius*	F
Painted Bunting	*Pandion haliaetus*	O
Palm Warbler	*Seiurus aurocapilla*	F
Pelagic Cormorant	*Troglodytes pacificus*	W
Peregrine Falcon	*Empidonax difficilis*	O
Phainopepla	*Passerina ciris*	O
Philadelphia Vireo	*Setophaga palmarum*	F
Pied-billed Grebe	*Phalacrocorax pelagicus*	W
Pileated Woodpecker	*Falco peregrinus*	F
Pine Grosbeak	*Phainopepla nitens*	F
Pine Siskin	*Vireo philadelphicus*	F
Pine Warbler	*Podilymbus podiceps*	F
Pinyon Jay	*Dryocopus pileatus*	FE
Plumbeous Vireo	*Pinicola enucleator*	F

Common Name	Scientific Name	Breeding Habitat
Prairie Falcon	*Spinus pinus*	O
Prairie Warbler	*Setophaga pinus*	O
Prothonotary Warbler	*Gymnorhinus cyanocephalus*	F
Purple Finch	*Vireo plumbeus*	F
Purple Gallinule	*Falco mexicanus*	W
Purple Martin	*Setophaga discolor*	FE
Pygmy Nuthatch	*Protonotaria citrea*	F
Red Crossbill	*Haemorhous purpureus*	F
Red-bellied Woodpecker	*Porphyrio martinicus*	F
Red-breasted Merganser	*Progne subis*	W
Red-breasted Nuthatch	*Sitta pygmaea*	F
Red-breasted Sapsucker	*Loxia curvirostra*	F
Red-cockaded Woodpecker	*Melanerpes carolinus*	F
Red-eyed Vireo	*Mergus serrator*	F
Red-faced Warbler	*Sitta canadensis*	F
Redhead	*Sphyrapicus ruber*	W
Red-headed Woodpecker	*Dryobates borealis*	F
Red-naped Sapsucker	*Vireo olivaceus*	F
Red-necked Grebe	*Cardellina rubrifrons*	W
Red-shouldered Hawk	*Aythya americana*	F
Red-tailed Hawk	*Melanerpes erythrocephalus*	FE
Red-winged Blackbird	*Sphyrapicus nuchalis*	O
Ring-billed Gull	*Podiceps grisegena*	W
Ring-necked Duck	*Buteo lineatus*	W
Ring-necked Pheasant	*Buteo jamaicensis*	O
Rock Pigeon	*Agelaius phoeniceus*	O
Rock Wren	*Larus delawarensis*	O
Rose-breasted Grosbeak	*Aythya collaris*	F
Rough-legged Hawk	*Phasianus colchicus*	O
Ruby-crowned Kinglet	*Columba livia*	F
Ruby-throated Hummingbird	*Salpinctes obsoletus*	F
Ruddy Duck	*Pheucticus ludovicianus*	W
Ruffed Grouse	*Buteo lagopus*	F
Rufous Hummingbird	*Regulus calendula*	F
Rufous-crowned Sparrow	*Archilochus colubris*	O

Common Name	Scientific Name	Breeding Habitat
Rusty Blackbird	*Oxyura jamaicensis*	F
Sage Thrasher	*Bonasa umbellus*	O
Sandhill Crane	*Selasphorus rufus*	W
Savannah Sparrow	*Aimophila ruficeps*	O
Say's Phoebe	*Euphagus carolinus*	O
Scarlet Tanager	*Oreoscoptes montanus*	F
Scissor-tailed Flycatcher	*Antigone canadensis*	O
Scott's Oriole	*Passerculus sandwichensis*	F
Sedge Wren	*Sayornis saya*	O
Sharp-shinned Hawk	*Piranga olivacea*	F
Sharp-tailed Grouse	*Tyrannus forficatus*	O
Short-eared Owl	*Icterus parisorum*	O
Snowy Egret	*Cistothorus platensis*	W
Solitary Sandpiper	*Accipiter striatus*	W
Song Sparrow	*Tympanuchus phasianellus*	O
Sooty Grouse	*Asio flammeus*	F
Sora	*Egretta thula*	W
Spotted Owl	*Tringa solitaria*	N
Spotted Sandpiper	*Melospiza melodia*	W
Spotted Towhee	*Dendragapus fuliginosus*	F
Spruce Grouse	*Porzana carolina*	F
Steller's Jay	*Strix occidentalis*	F
Summer Tanager	*Actitis macularius*	F
Swainson's Hawk	*Pipilo maculatus*	O
Swainson's Thrush	*Falcipennis canadensis*	F
Swainson's Warbler	*Cyanocitta stelleri*	F
Swallow-tailed Kite	*Piranga rubra*	FE
Swamp Sparrow	*Buteo swainsoni*	O
Tennessee Warbler	*Catharus ustulatus*	F
Townsend's Solitaire	*Limnothlypis swainsonii*	F
Townsend's Warbler	*Elanoides forficatus*	F
Tree Swallow	*Melospiza georgiana*	FE
Tricolored Blackbird	*Leiothlypis peregrina*	O
Tricolored Heron	*Myadestes townsendi*	W
Trumpeter Swan	*Setophaga townsendi*	W

Common Name	Scientific Name	Breeding Habitat
Tufted Titmouse	*Tachycineta bicolor*	F
Turkey Vulture	*Agelaius tricolor*	O
Varied Thrush	*Egretta tricolor*	F
Vaux's Swift	*Cygnus buccinator*	FE
Veery	*Baeolophus bicolor*	F
Vesper Sparrow	*Cathartes aura*	O
Violet-green Swallow	*Ixoreus naevius*	FE
Virginia Rail	*Chaetura vauxi*	W
Virginia's Warbler	*Catharus fuscescens*	F
Warbling Vireo	*Pooecetes gramineus*	F
Western Bluebird	*Tachycineta thalassina*	FE
Western Grebe	*Rallus limicola*	W
Western Gull	*Leiothlypis virginiae*	W
Western Kingbird	*Vireo gilvus*	O
Western Meadowlark	*Sialia mexicana*	O
Western Screech-Owl	*Aechmophorus occidentalis*	N
Western Tanager	*Larus occidentalis*	F
Western Wood-Pewee	*Tyrannus verticalis*	F
White Ibis	*Sturnella neglecta*	W
White-breasted Nuthatch	*Megascops kennicottii*	F
White-crowned Sparrow	*Piranga ludoviciana*	F
White-eyed Vireo	*Contopus sordidulus*	F
White-headed Woodpecker	*Eudocimus albus*	F
White-tailed Kite	*Sitta carolinensis*	O
White-tailed Ptarmigan	*Zonotrichia leucophrys*	O
White-throated Sparrow	*Vireo griseus*	F
White-throated Swift	*Dryobates albolarvatus*	O
White-winged Crossbill	*Elanus leucurus*	F
White-winged Dove	*Lagopus leucura*	F
Wild Turkey	*Zonotrichia albicollis*	O
Willet	*Aeronautes saxatalis*	W
Williamson's Sapsucker	*Loxia leucoptera*	F
Willow Flycatcher	*Zenaida asiatica*	FE
Wilson's Phalarope	*Meleagris gallopavo*	W
Wilson's Snipe	*Tringa semipalmata*	W

Common Name	Scientific Name	Breeding Habitat
Wilson's Warbler	*Sphyrapicus thyroideus*	F
Winter Wren	*Empidonax traillii*	F
Wood Duck	*Phalaropus tricolor*	W
Wood Stork	*Gallinago delicata*	W
Wood Thrush	*Cardellina pusilla*	F
Worm-eating Warbler	*Troglodytes hiemalis*	F
Wrentit	*Aix sponsa*	O
Yellow Warbler	*Mycteria americana*	O
Yellow-bellied Flycatcher	*Hylocichla mustelina*	F
Yellow-bellied Sapsucker	*Helmitheros vermivorum*	F
Yellow-billed Cuckoo	*Chamaea fasciata*	F
Yellow-breasted Chat	*Setophaga petechia*	O
Yellow-crowned Night-Heron	*Empidonax flaviventris*	W
Yellow-headed Blackbird	*Sphyrapicus varius*	O
Yellow-rumped Warbler	*Coccyzus americanus*	F
Yellow-throated Vireo	*Icteria virens*	F
Yellow-throated Warbler	*Nyctanassa violacea*	F
Zone-tailed Hawk	*Xanthocephalus xanthocephalus*	FE

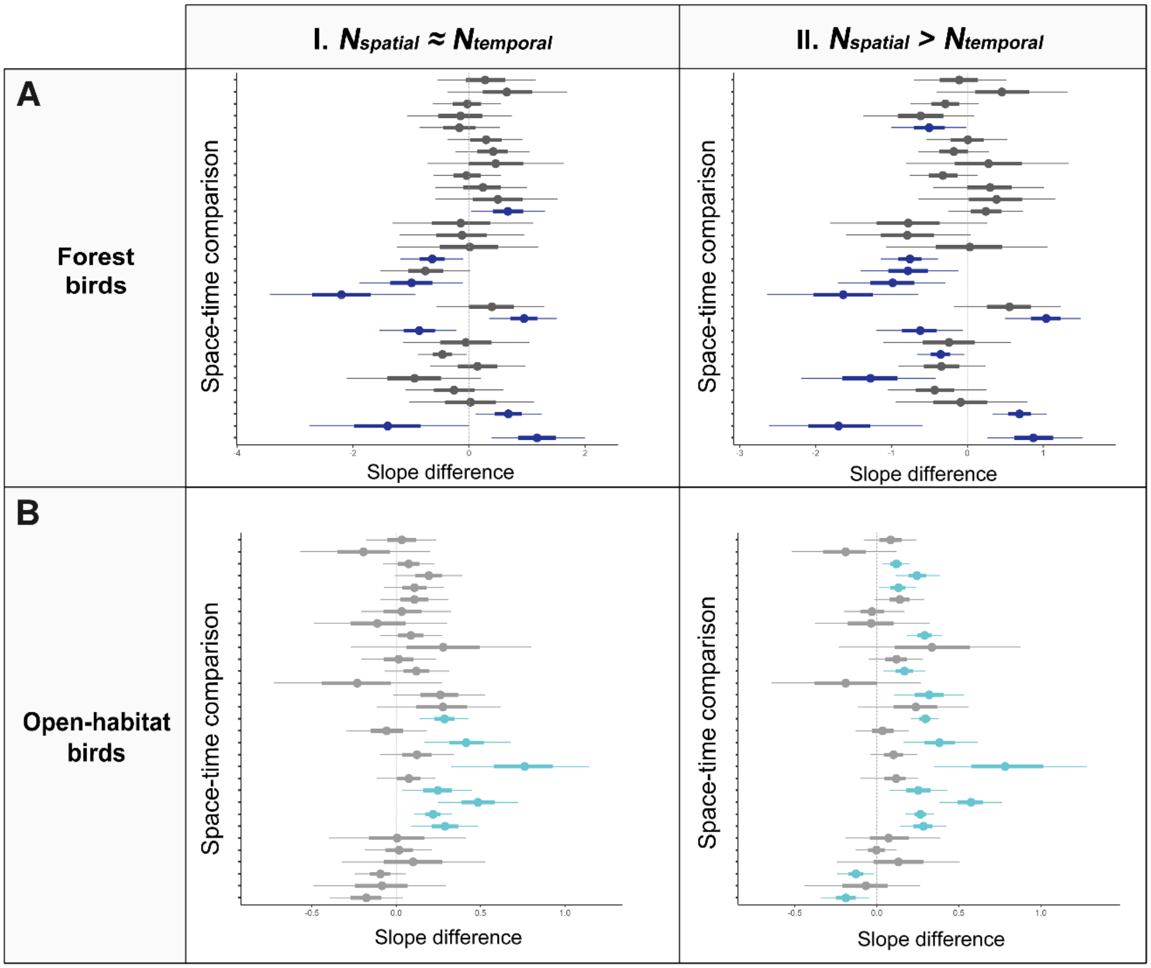


Figure A. Posterior difference between temporal slopes and spatial slopes (= $temporal\ slope\ -\ spatial\ slope$) measuring the effect of forest cover on mean forest (A) and open-habitat (B) bird species richness over time at a temporal site from 2000 to 2019 and in space across neighbouring spatial sites in 2019, respectively. The 31 space-time comparisons are listed in order from top-to-bottom. Spatial slopes were estimated twice: once where the number of spatial sites informing the spatial slope matched with the number of years informing the corresponding temporal slope (scenario I) and again where the maximum number of eligible spatial sites was used to inform the spatial slope (scenario II). Space-time comparisons where the difference between temporal and spatial slopes do not overlap with zero are highlighted in colour, representing comparisons where the estimated forest cover effects in time and space are significantly unequal and thus, where space-for-time substitution fails most notably.

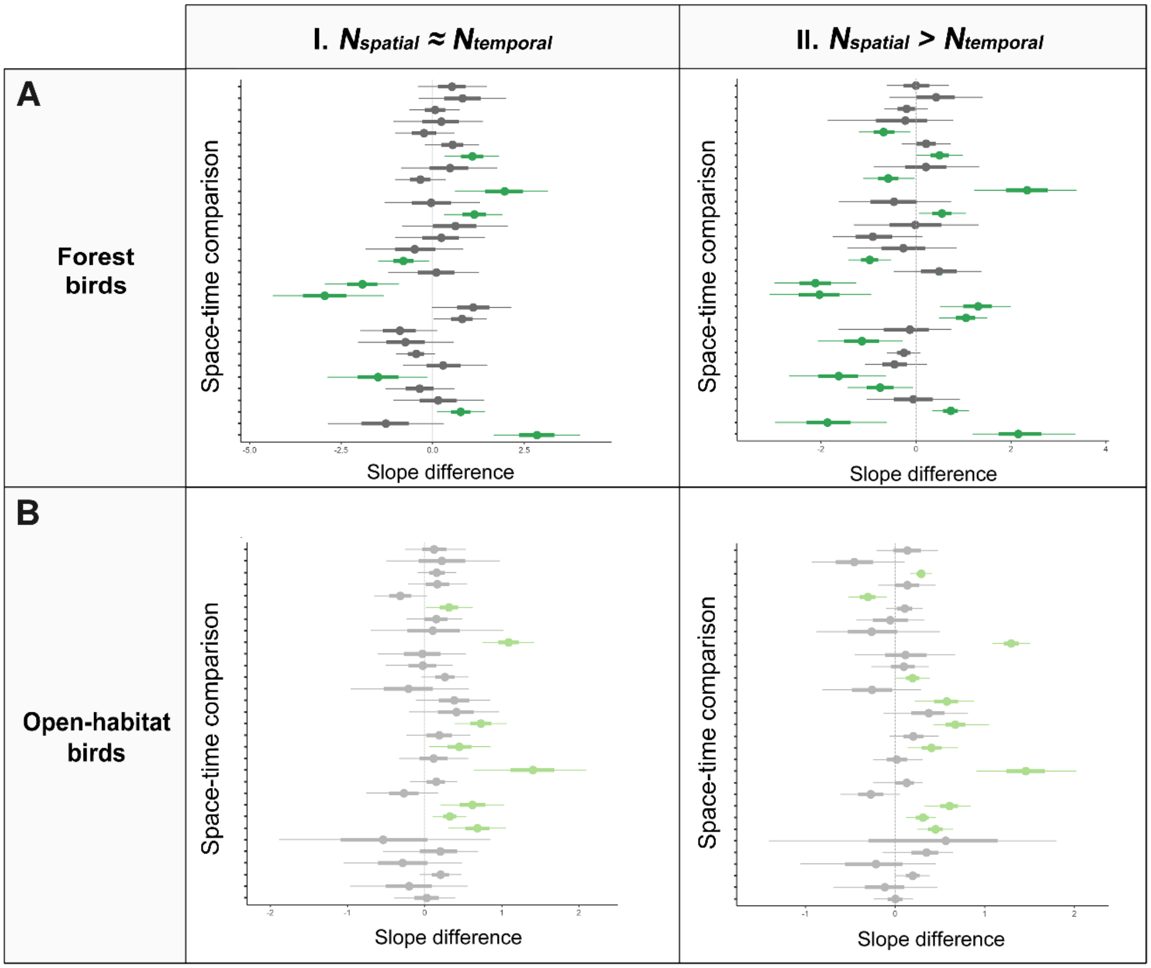
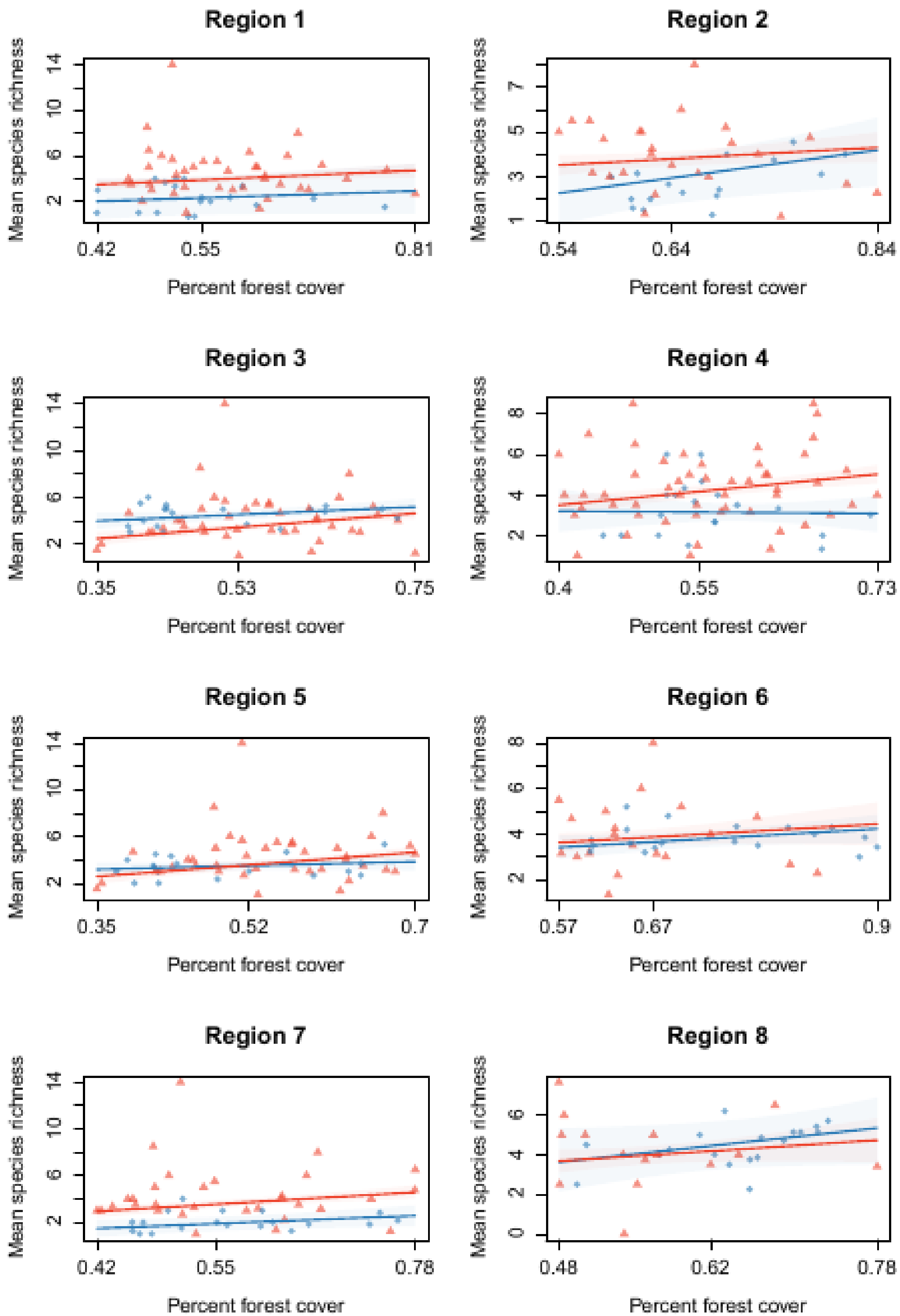


Figure B. Posterior difference between temporal slopes and spatial slopes (= $temporal\ slope\ -\ spatial\ slope$), each measuring the effect of forest cover on mean forest (A) and open-habitat (B) bird abundance over time at a temporal site from 2000 to 2019 and in space across neighbouring spatial sites in 2019, respectively. The 31 space-time comparisons are listed from 1 to 31. Spatial slopes were estimated twice: once where the number of spatial sites informing the spatial slope matched with the number of years informing the corresponding temporal slope (scenario I) and again where the maximum number of eligible spatial sites was used to inform the spatial slope (scenario II). Space-time comparisons where the difference between temporal and spatial slopes do not overlap with zero are highlighted in colour, representing comparisons where the estimated forest cover effects in time and space are significantly unequal and thus, where space-for-time substitution fails most notably.

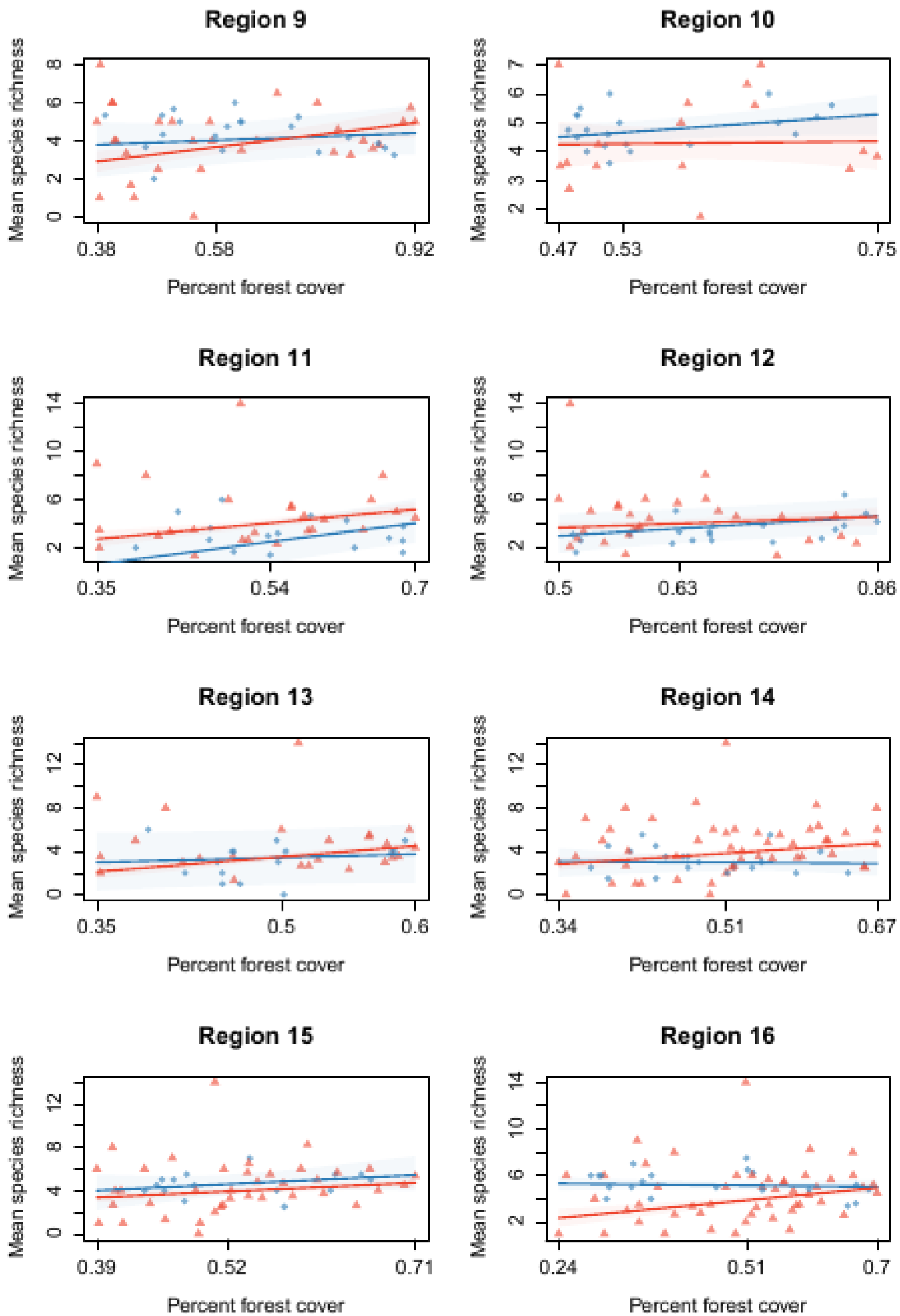
Table C. Slope parameter coefficient estimates measuring the effect of forest cover on forest bird mean species richness over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope") for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by the full number of available spatial sites within each space-time comparison, which may exceed the number of years informing the corresponding temporal slope.

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
1	0.278933	-0.3466	0.943553	0.386921	0.032148	0.733342
2	0.774225	-0.15427	1.69073	0.317686	-0.12397	0.756448
3	0.370741	-0.06279	0.804842	0.664346	0.330418	0.997867
4	-0.04389	-0.89237	0.73565	0.577889	0.247724	0.910991
5	0.226009	-0.22886	0.690577	0.725966	0.361677	1.078408
6	0.295237	-0.10375	0.687678	0.294791	-0.20201	0.801913
7	0.373589	-0.06908	0.799901	0.555213	0.195055	0.915207
8	0.706865	-0.37108	1.785733	0.432957	-0.2497	1.123258
9	0.140236	-0.30033	0.615607	0.460933	0.158504	0.751327
10	0.339089	-0.1328	0.792579	0.047844	-0.67613	0.786975
11	1.211634	0.049915	2.056016	0.871901	0.430948	1.291691
12	0.554398	0.113926	1.006626	0.308422	-0.10909	0.717939
13	0.380815	-0.7271	1.498764	1.158292	0.642847	1.6445
14	-0.07142	-1.0022	0.876141	0.716647	0.376949	1.045739
15	0.542172	-0.70613	1.714608	0.520334	0.174423	0.866899
16	-0.073	-0.38703	0.230797	0.686548	0.344049	1.025584
17	-0.43343	-0.94401	0.091186	0.342848	-0.25347	0.906375
18	-0.7612	-1.5185	-0.01744	0.231372	-0.19736	0.670591
19	-1.21934	-2.32723	-0.08626	0.419021	-0.01989	0.854529
20	0.704497	-0.14818	1.483568	0.159414	-0.12732	0.446761
21	1.252641	0.663909	1.723993	0.230196	-0.05943	0.523226
22	-0.33882	-0.97291	0.279871	0.290297	0.047222	0.528971

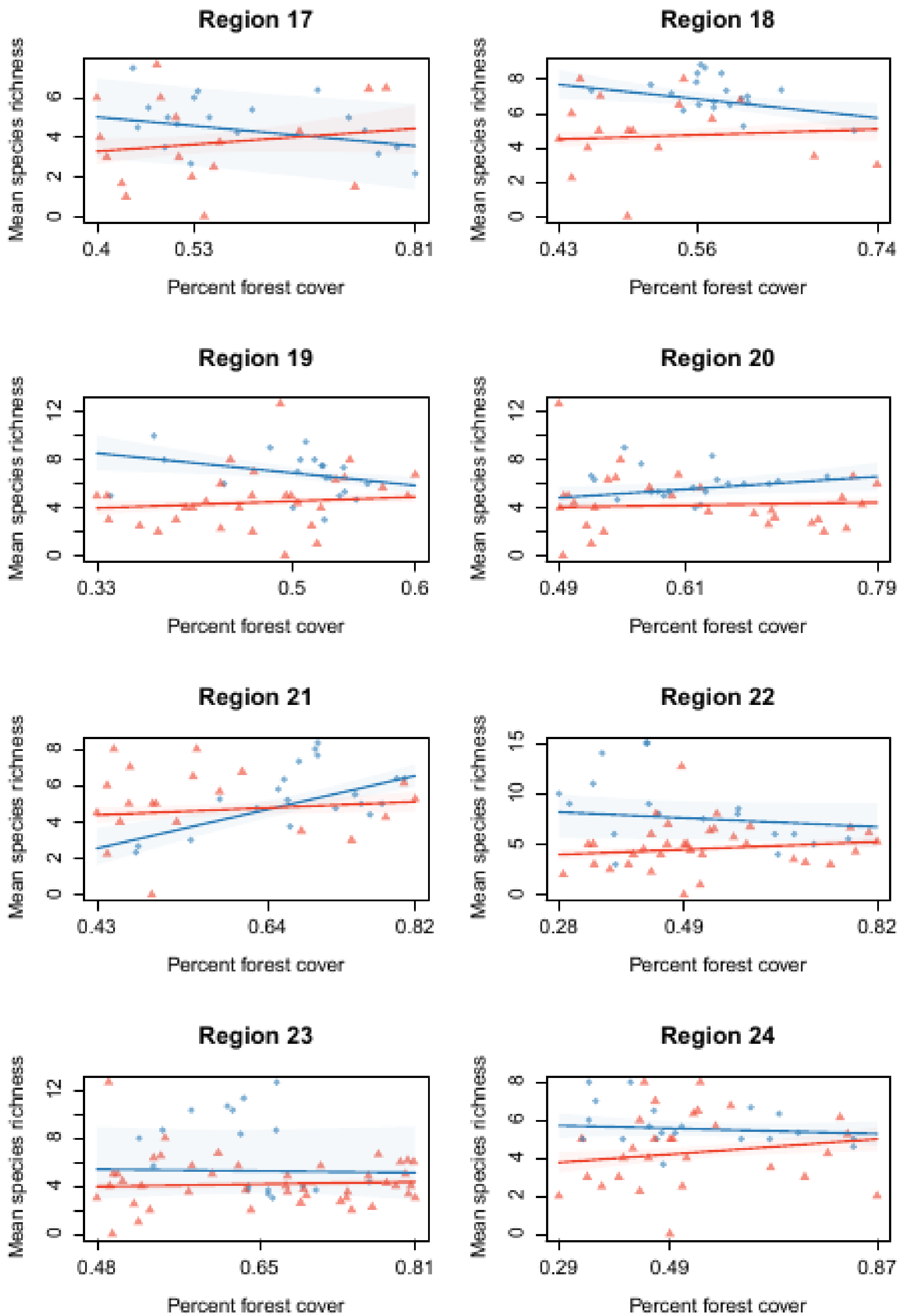
	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
23	-0.10051	-1.07048	0.849327	0.147227	-0.09578	0.388981
24	-0.09222	-0.37691	0.184895	0.261326	0.00391	0.518058
25	-0.13512	-0.70491	0.459476	0.200449	-0.16715	0.575372
26	-0.84625	-1.88889	0.136816	0.441905	0.104235	0.78099
27	-0.33407	-1.00534	0.428512	0.088626	-0.2172	0.39618
28	0.121028	-0.86277	1.132793	0.206127	-0.01392	0.426654
29	0.92346	0.544321	1.302991	0.23533	0.024709	0.454321
30	-1.39432	-2.48226	-0.09927	0.2712	0.009957	0.523926
31	0.988601	0.352197	1.647955	0.112716	-0.265	0.479673



Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
Region 8
Mean species richness
Percent forest cover
0.42
0.55
0.81
0.54
0.64
0.84
0.35
0.53
0.75
0.4
0.55
0.73
0.35
0.52
0.7
0.57
0.67
0.9
0.42
0.55
0.78
0.48
0.62
0.78



Region 9
Mean species richness
0
2
4
6
8
0.38
0.58
0.92
Percent forest cover
Region 10
Mean species richness
2
3
4
5
6
7
0.47
0.53
0.75
Percent forest cover
Region 11
Mean species richness
2
6
10
14
0.35
0.54
0.7
Percent forest cover
Region 12
Mean species richness
2
6
10
14
0.5
0.63
0.86
Percent forest cover
Region 13
Mean species richness
0
4
8
12
0.35
0.5
0.6
Percent forest cover
Region 14
Mean species richness
0
4
8
12
0.34
0.51
0.67
Percent forest cover
Region 15
Mean species richness
0
4
8
12
0.39
0.52
0.71
Percent forest cover
Region 16
Mean species richness
2
6
10
14
0.24
0.51
0.7
Percent forest cover



Region 17
Region 18
Region 19
Region 20
Region 21
Region 22
Region 23
Region 24
Mean species richness
Percent forest cover

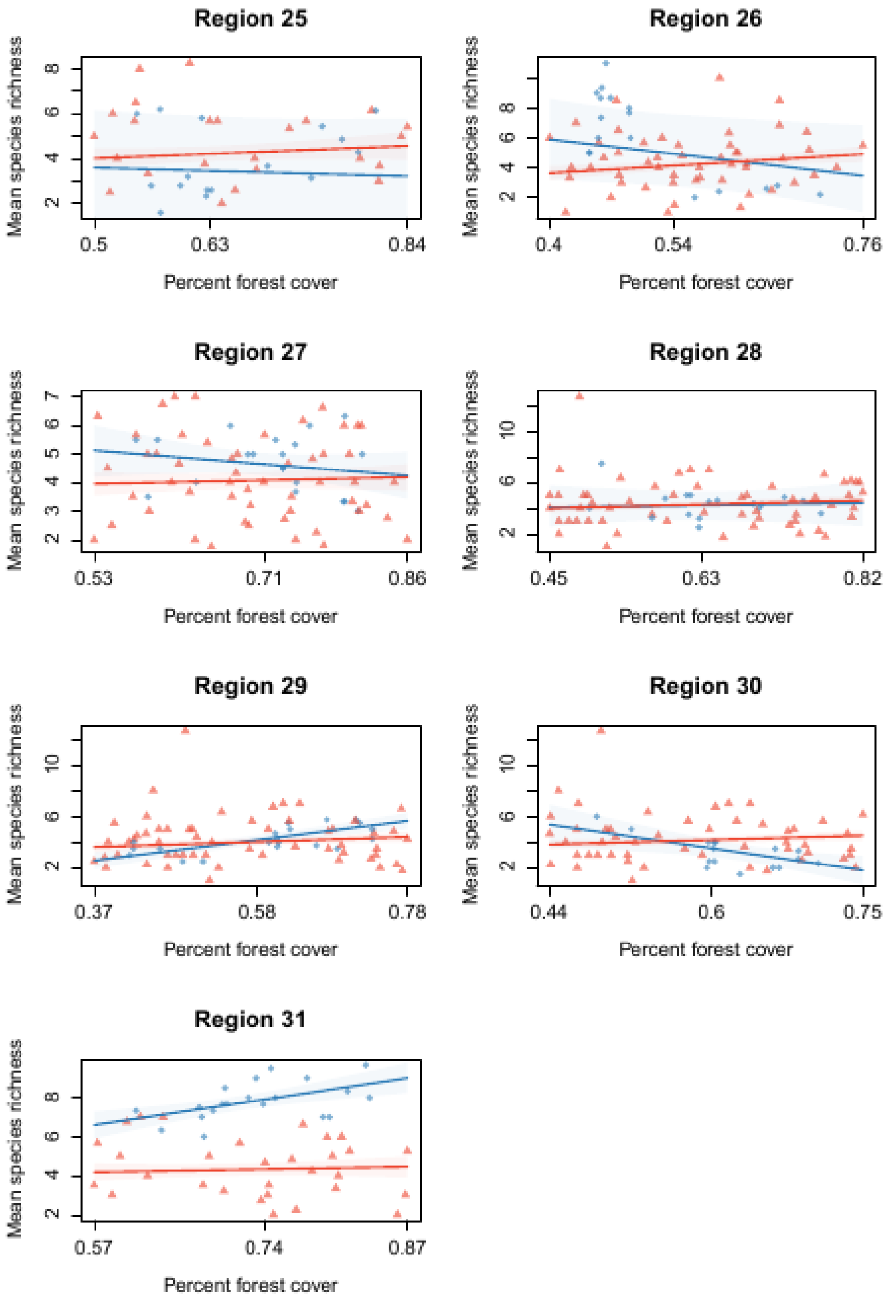
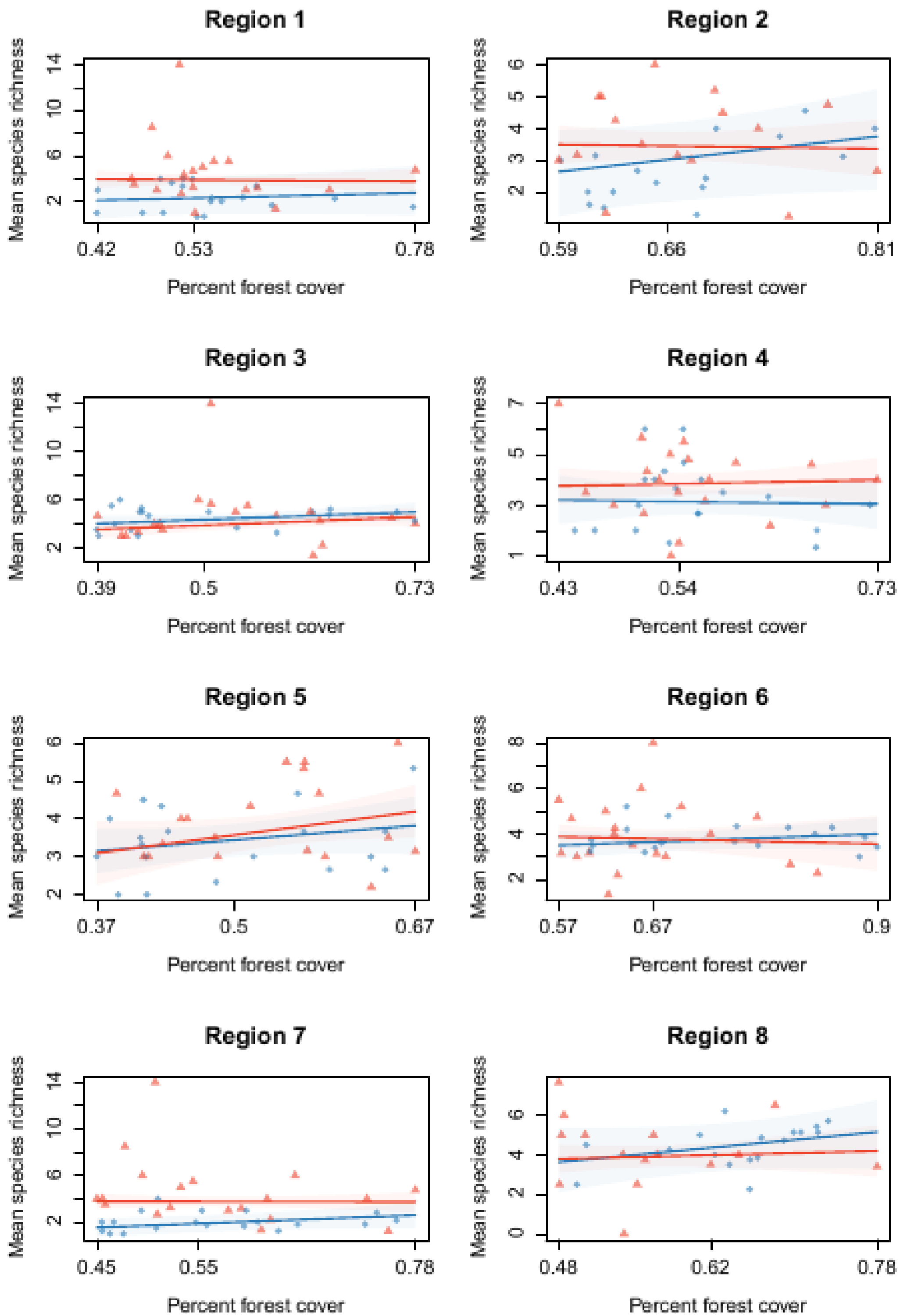


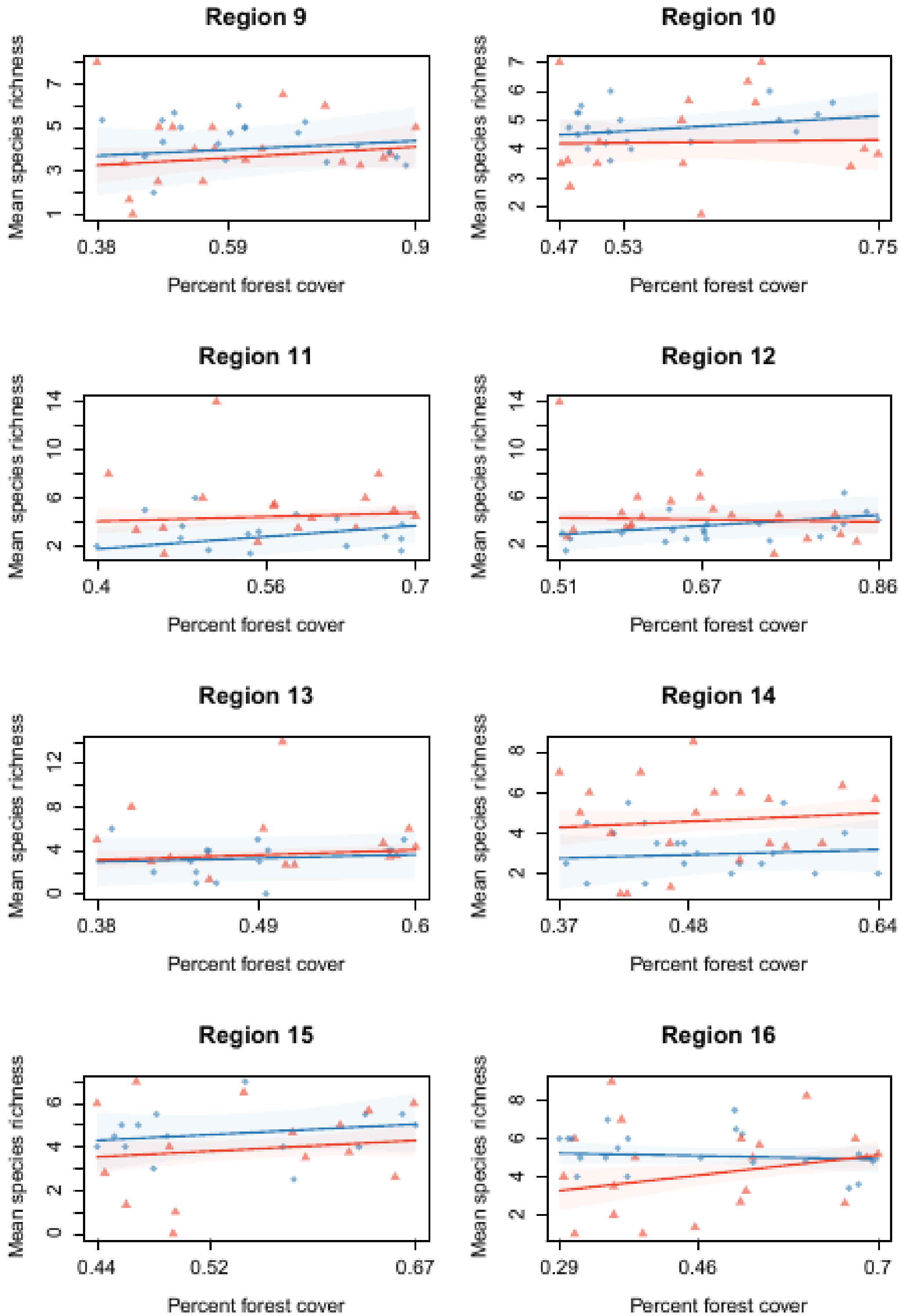
Figure C. Slope estimates (with 95% percentile interval shaded) measuring the effect of forest cover on forest bird mean species richness over time at a temporal site from 2000 to 2019 (in blue) and in space across a set of neighbouring spatial sites in 2019 (in red) for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by the full number of available spatial sites within each space-time comparison, which may exceed the number of years informing the corresponding temporal slope.

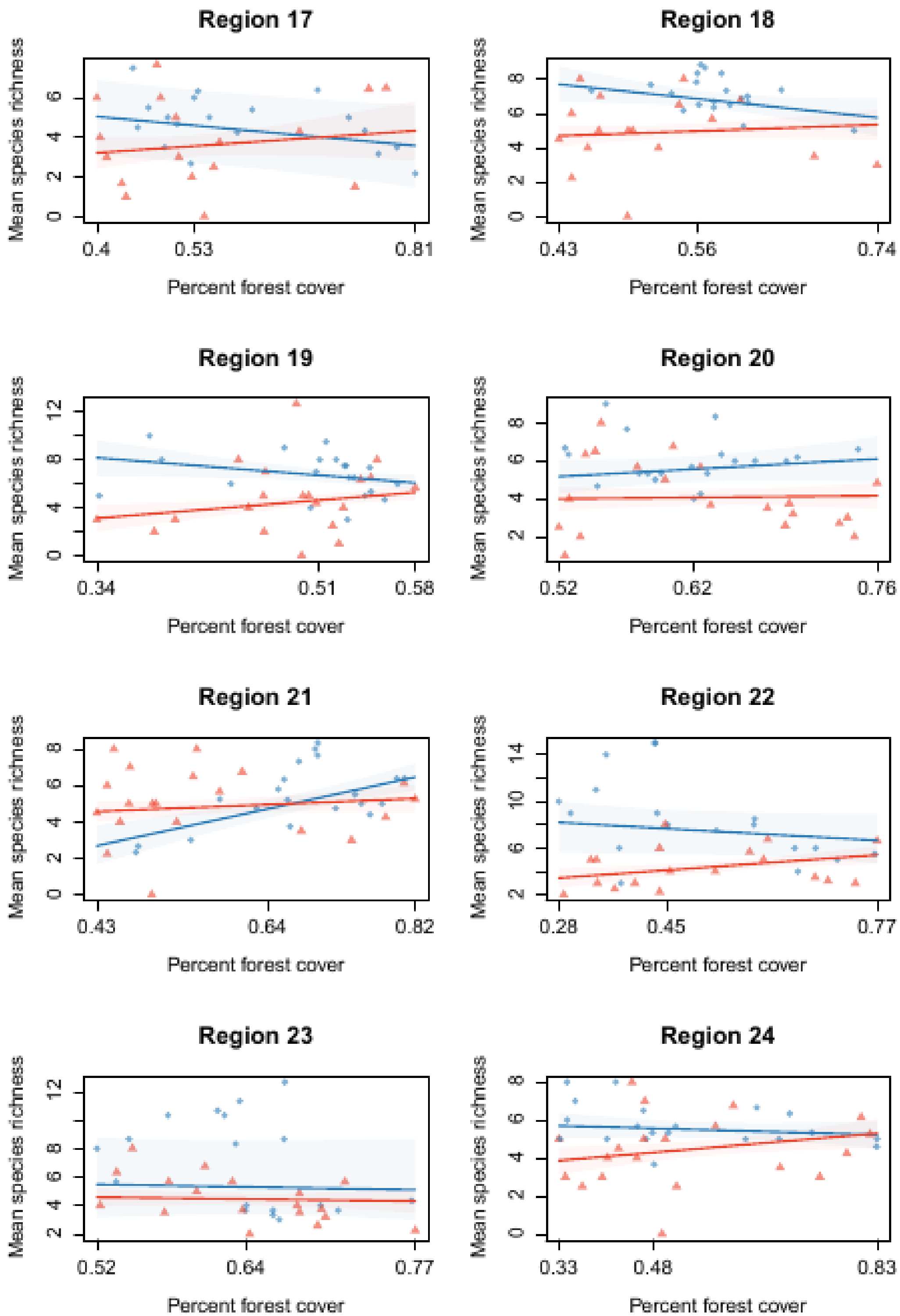
Table D. Slope parameter coefficient estimates measuring the effect of forest cover on forest bird mean species richness over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope") for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by a subset number of eligible spatial sites equal to the number of years informing the corresponding temporal slope.

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
1	0.21658	-0.5305	1.003452	-0.06648	-0.73922	0.597158
2	0.589416	-0.41435	1.577536	-0.07028	-0.83355	0.715811
3	0.34019	-0.12066	0.813527	0.377508	-0.18311	0.935251
4	-0.06314	-0.94849	0.764872	0.097074	-0.58532	0.786763
5	0.271383	-0.23531	0.792587	0.438829	-0.20053	1.071278
6	0.174669	-0.28149	0.625919	-0.10943	-0.75155	0.549524
7	0.389338	-0.14674	0.917493	-0.01536	-0.57367	0.551602
8	0.612538	-0.52149	1.758062	0.15801	-0.65951	0.99369
9	0.159915	-0.3589	0.702113	0.1981	-0.25746	0.658512
10	0.279053	-0.27252	0.82271	0.05429	-0.72722	0.862136
11	0.760744	-0.31521	1.681288	0.271647	-0.52853	1.016087
12	0.555849	0.047807	1.056569	-0.11308	-0.72074	0.503592
13	0.374161	-0.80297	1.622343	0.510513	-0.3112	1.29062
14	0.187604	-0.86569	1.228732	0.316077	-0.4027	1.047632
15	0.389331	-0.90178	1.595733	0.399041	-0.32622	1.135353
16	-0.09492	-0.44655	0.263856	0.544821	0.006468	1.08731
17	-0.42667	-1.01221	0.166577	0.325461	-0.39118	1.024592
18	-0.74591	-1.62614	0.156423	0.250493	-0.29849	0.826748
19	-1.07803	-2.20344	0.089469	1.116421	0.145242	2.053296
20	0.457223	-0.5401	1.388983	0.07562	-0.52105	0.678287
21	1.159671	0.547579	1.705899	0.219762	-0.18179	0.619472
22	-0.37999	-1.05199	0.261462	0.487711	0.085121	0.907158
23	-0.18589	-1.24946	0.855354	-0.1319	-0.86769	0.604803

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
24	-0.11529	-0.4489	0.219149	0.348015	-0.02477	0.728951
25	-0.02151	-0.68533	0.697175	-0.16748	-0.89735	0.541018
26	-0.95154	-2.05625	0.118814	-0.0036	-0.86397	0.850687
27	-0.23963	-0.96646	0.52698	0.016644	-0.66511	0.689737
28	-0.03464	-1.10809	1.058012	-0.06165	-0.76486	0.635535
29	0.886321	0.440188	1.358131	0.21123	-0.30289	0.718407
30	-1.17779	-2.3633	0.146941	0.221378	-0.82499	1.276098
31	0.963182	0.26797	1.683838	-0.21175	-0.89246	0.452732


Region 1
Mean species richness
2
6
10
14
0.42
0.53
0.78
Percent forest cover
Region 2
Mean species richness
2
3
4
5
6
0.59
0.66
0.81
Percent forest cover
Region 3
Mean species richness
2
6
10
14
0.39
0.5
0.73
Percent forest cover
Region 4
Mean species richness
1
3
5
7
0.43
0.54
0.73
Percent forest cover
Region 5
Mean species richness
2
3
4
5
6
0.37
0.5
0.67
Percent forest cover
Region 6
Mean species richness
2
4
6
8
0.57
0.67
0.9
Percent forest cover
Region 7
Mean species richness
2
6
10
14
0.45
0.55
0.78
Percent forest cover
Region 8
Mean species richness
0
2
4
6
0.48
0.62
0.78
Percent forest cover


Region 9
Mean species richness
1
3
5
7
0.38
0.59
0.9
Percent forest cover
Region 10
Mean species richness
2
3
4
5
6
7
0.47
0.53
0.75
Percent forest cover
Region 11
Mean species richness
2
6
10
14
0.4
0.56
0.7
Percent forest cover
Region 12
Mean species richness
2
6
10
14
0.51
0.67
0.86
Percent forest cover
Region 13
Mean species richness
0
4
8
12
0.38
0.49
0.6
Percent forest cover
Region 14
Mean species richness
2
4
6
8
0.37
0.48
0.64
Percent forest cover
Region 15
Mean species richness
0
2
4
6
0.44
0.52
0.67
Percent forest cover
Region 16
Mean species richness
2
4
6
8
0.29
0.46
0.7
Percent forest cover


Region 17
Mean species richness
0 2 4 6
0.4 0.53 0.81
Percent forest cover
Region 18
Mean species richness
0 2 4 6 8
0.43 0.56 0.74
Percent forest cover
Region 19
Mean species richness
0 4 8 12
0.34 0.51 0.58
Percent forest cover
Region 20
Mean species richness
2 4 6 8
0.52 0.62 0.76
Percent forest cover
Region 21
Mean species richness
0 2 4 6 8
0.43 0.64 0.82
Percent forest cover
Region 22
Mean species richness
2 6 10 14
0.28 0.45 0.77
Percent forest cover
Region 23
Mean species richness
2 4 6 8 12
0.52 0.64 0.77
Percent forest cover
Region 24
Mean species richness
0 2 4 6 8
0.33 0.48 0.83
Percent forest cover

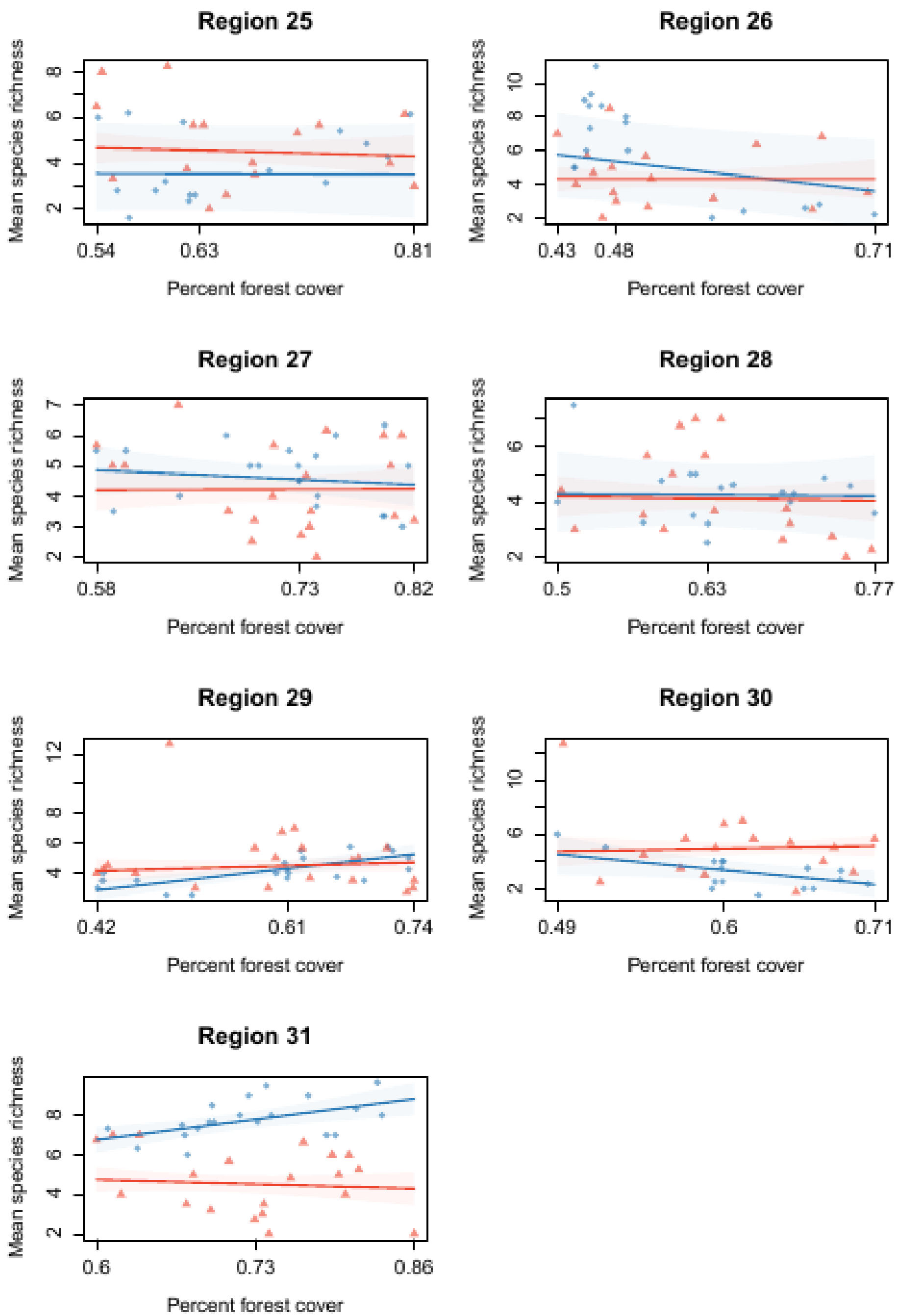
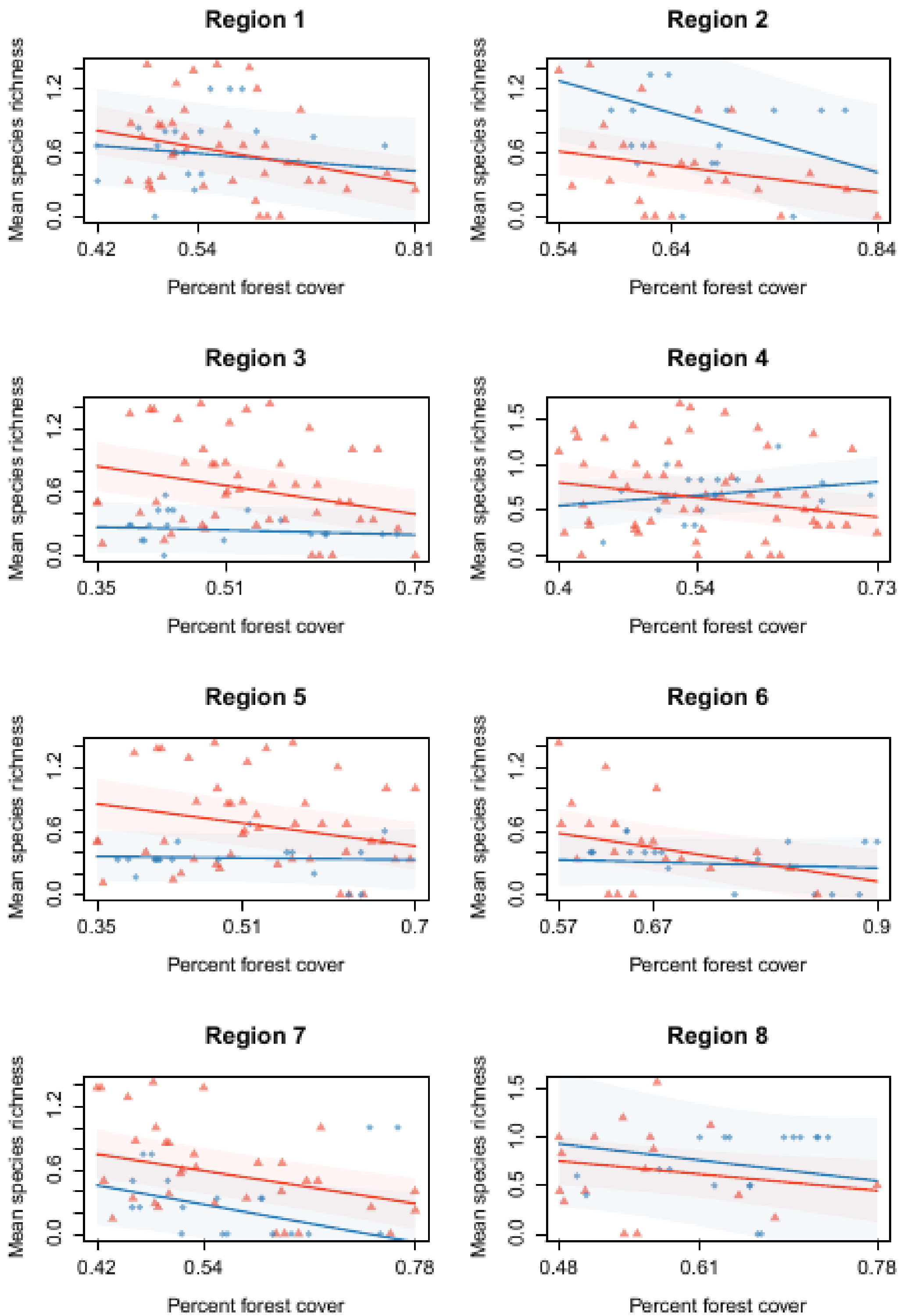


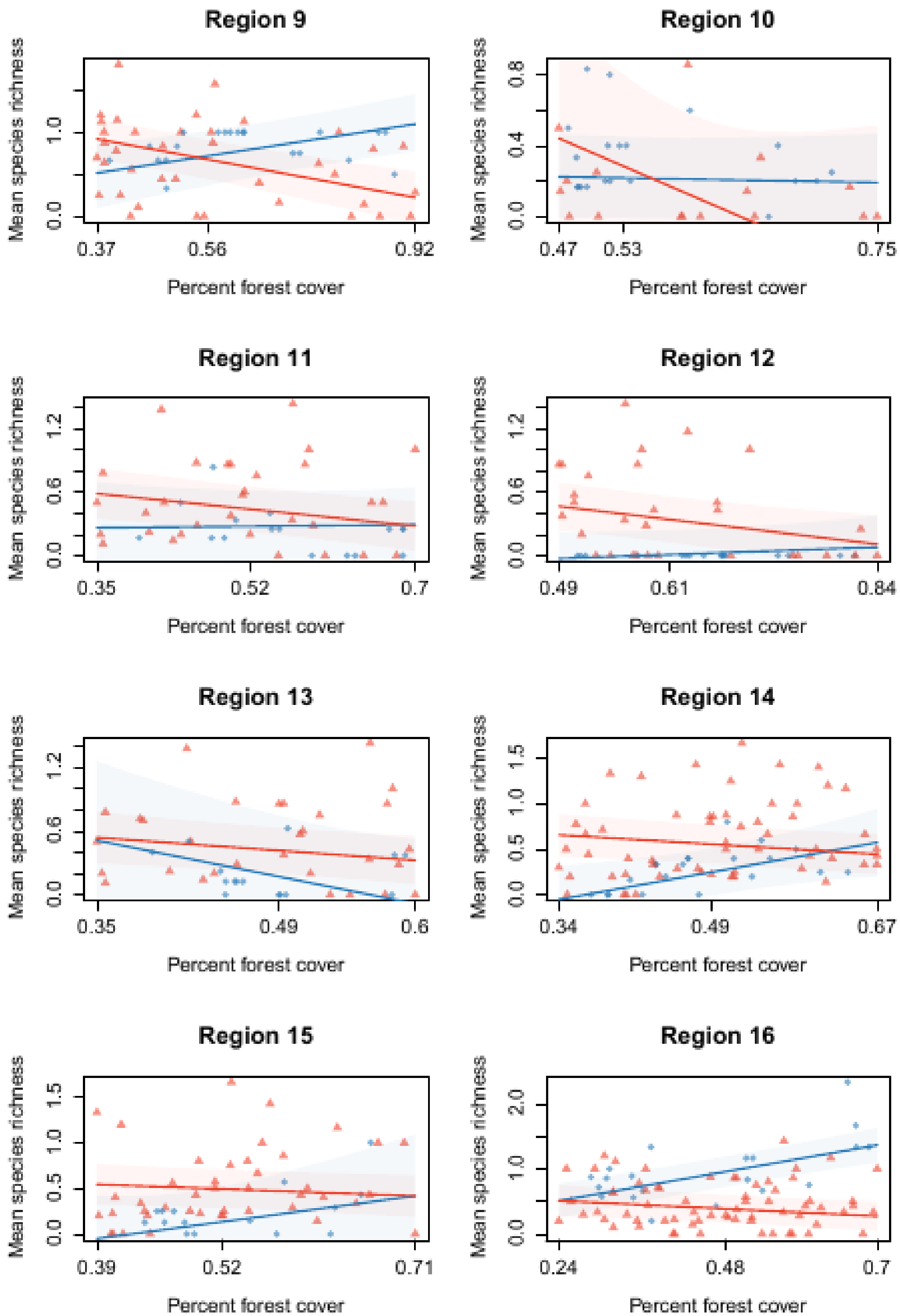
Figure D. Slope estimates (with 95% percentile interval shaded) measuring the effect of forest cover on forest bird mean species richness over time at a temporal site from 2000 to 2019 (in blue) and in space across a set of neighbouring spatial sites in 2019 (in red) for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by a subset number of eligible spatial sites equal to the number of years informing the corresponding temporal slope.

Table E. Slope parameter coefficient estimates measuring the effect of forest cover on open-habitat bird mean species richness over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope") for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by the full number of available spatial sites within each space-time comparison, which may exceed the number of years informing the corresponding temporal slope.

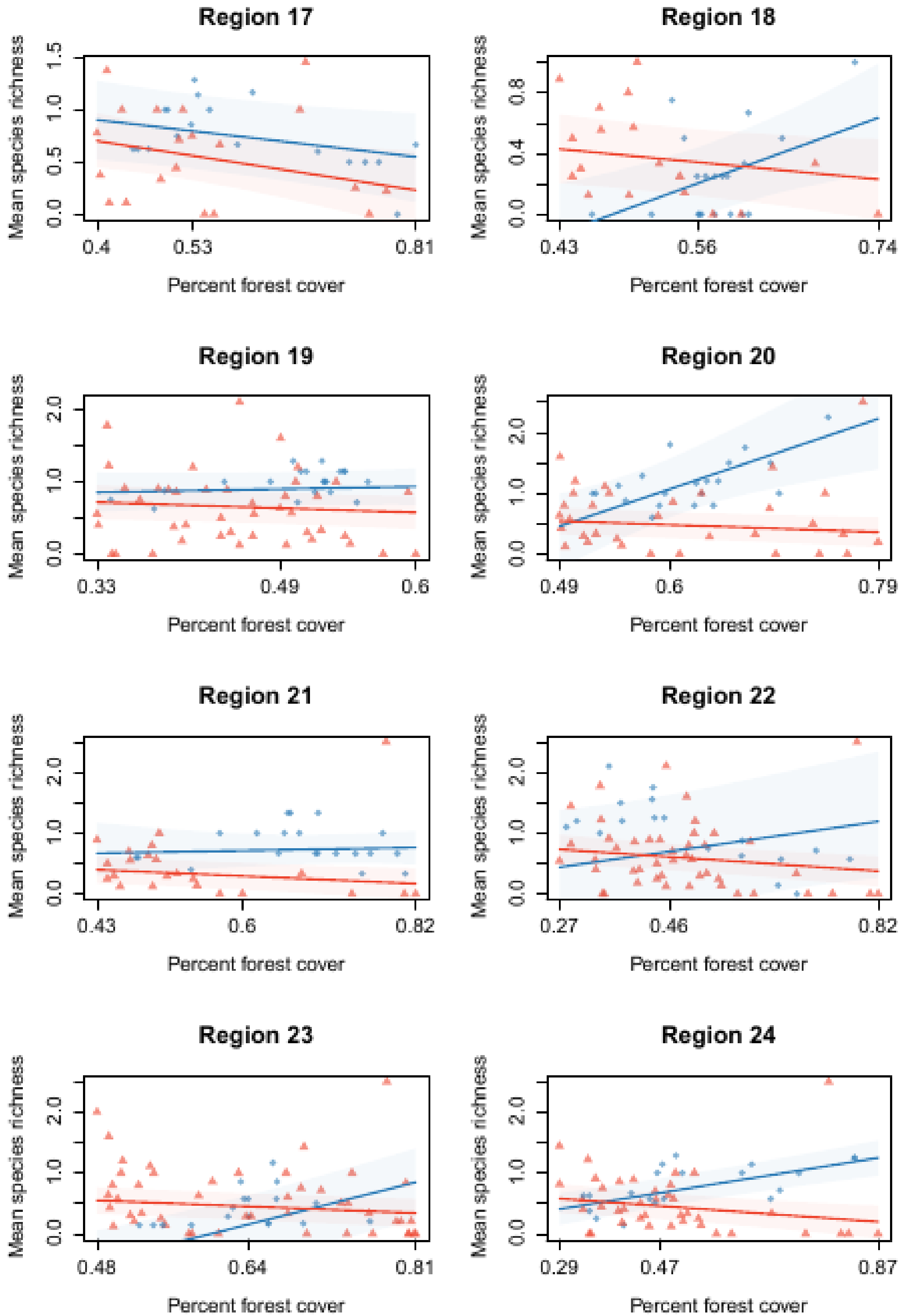
	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
1	-0.07619	-0.25735	0.095207	-0.15926	-0.24402	-0.07319
2	-0.35409	-0.72389	-0.00014	-0.15801	-0.26778	-0.04642
3	-0.02311	-0.09824	0.05145	-0.14096	-0.2105	-0.07091
4	0.100952	-0.03282	0.251073	-0.14613	-0.22811	-0.06293
5	-0.0106	-0.12672	0.095465	-0.14034	-0.21372	-0.06667
6	-0.02873	-0.17041	0.100728	-0.16712	-0.29518	-0.04184
7	-0.18563	-0.38064	0.056726	-0.16074	-0.24271	-0.07856
8	-0.16049	-0.53621	0.243369	-0.12822	-0.2928	0.027306
9	0.132259	0.027492	0.235614	-0.1585	-0.23867	-0.0828
10	-0.01465	-0.13779	0.105913	-0.34657	-0.98077	0.324686
11	0.010306	-0.18039	0.196131	-0.10788	-0.19201	-0.02346
12	0.03944	-0.08652	0.164136	-0.12853	-0.22789	-0.03054
13	-0.29343	-0.82475	0.261263	-0.10512	-0.21058	0.00663
14	0.237874	-0.00602	0.48438	-0.08002	-0.1539	-0.00456
15	0.182017	-0.22966	0.565442	-0.04923	-0.12287	0.025798
16	0.230747	0.145677	0.311078	-0.06377	-0.1311	0.00152
17	-0.10709	-0.23668	0.026455	-0.14279	-0.29392	0.009513
18	0.304791	0.065862	0.565667	-0.07976	-0.18156	0.022989
19	0.036462	-0.10379	0.177652	-0.06555	-0.15776	0.029813
20	0.721946	0.21179	1.262787	-0.07483	-0.14585	-0.0034
21	0.029383	-0.21885	0.181019	-0.07282	-0.15166	0.005581
22	0.172049	-0.02806	0.37539	-0.08186	-0.14834	-0.01437

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
23	0.494787	0.272697	0.717609	-0.07769	-0.13796	-0.019
24	0.182187	0.099852	0.255027	-0.08222	-0.14882	-0.013
25	0.20101	0.051199	0.339395	-0.08092	-0.16637	0.002536
26	-0.05368	-0.36492	0.317588	-0.13499	-0.22022	-0.05038
27	-0.094	-0.21522	0.030663	-0.09167	-0.17265	-0.01335
28	0.058555	-0.38761	0.498022	-0.07236	-0.13121	-0.01369
29	-0.19651	-0.31295	-0.08052	-0.06864	-0.129	-0.00772
30	-0.1301	-0.56849	0.274013	-0.05583	-0.12069	0.008917
31	-0.26855	-0.42197	-0.12442	-0.07892	-0.1754	0.018167


Region 1
Mean species richness
0.0
0.6
1.2
0.42
0.54
0.81
Percent forest cover
Region 2
Mean species richness
0.0
0.6
1.2
0.54
0.64
0.84
Percent forest cover
Region 3
Mean species richness
0.0
0.6
1.2
0.35
0.51
0.75
Percent forest cover
Region 4
Mean species richness
0.0
0.5
1.0
1.5
0.4
0.54
0.73
Percent forest cover
Region 5
Mean species richness
0.0
0.6
1.2
0.35
0.51
0.7
Percent forest cover
Region 6
Mean species richness
0.0
0.6
1.2
0.57
0.67
0.9
Percent forest cover
Region 7
Mean species richness
0.0
0.6
1.2
0.42
0.54
0.78
Percent forest cover
Region 8
Mean species richness
0.0
0.5
1.0
1.5
0.48
0.61
0.78
Percent forest cover


Region 9
Mean species richness
0.0
1.0
0.37
0.56
0.92
Percent forest cover
Region 10
Mean species richness
0.0
0.4
0.8
0.47
0.53
0.75
Percent forest cover
Region 11
Mean species richness
0.0
0.6
1.2
0.35
0.52
0.7
Percent forest cover
Region 12
Mean species richness
0.0
0.6
1.2
0.49
0.61
0.84
Percent forest cover
Region 13
Mean species richness
0.0
0.6
1.2
0.35
0.49
0.6
Percent forest cover
Region 14
Mean species richness
0.0
0.5
1.0
1.5
0.34
0.49
0.67
Percent forest cover
Region 15
Mean species richness
0.0
0.5
1.0
1.5
0.39
0.52
0.71
Percent forest cover
Region 16
Mean species richness
0.0
1.0
2.0
0.24
0.48
0.7
Percent forest cover

\


Region 17
Region 18
Region 19
Region 20
Region 21
Region 22
Region 23
Region 24
Mean species richness
Percent forest cover
0.4
0.53
0.81
0.43
0.56
0.74
0.33
0.49
0.6
0.49
0.6
0.79
0.43
0.6
0.82
0.27
0.46
0.82
0.48
0.64
0.81
0.29
0.47
0.87
0.0
0.5
1.0
1.5
0.0
0.4
0.8
0.0
1.0
2.0

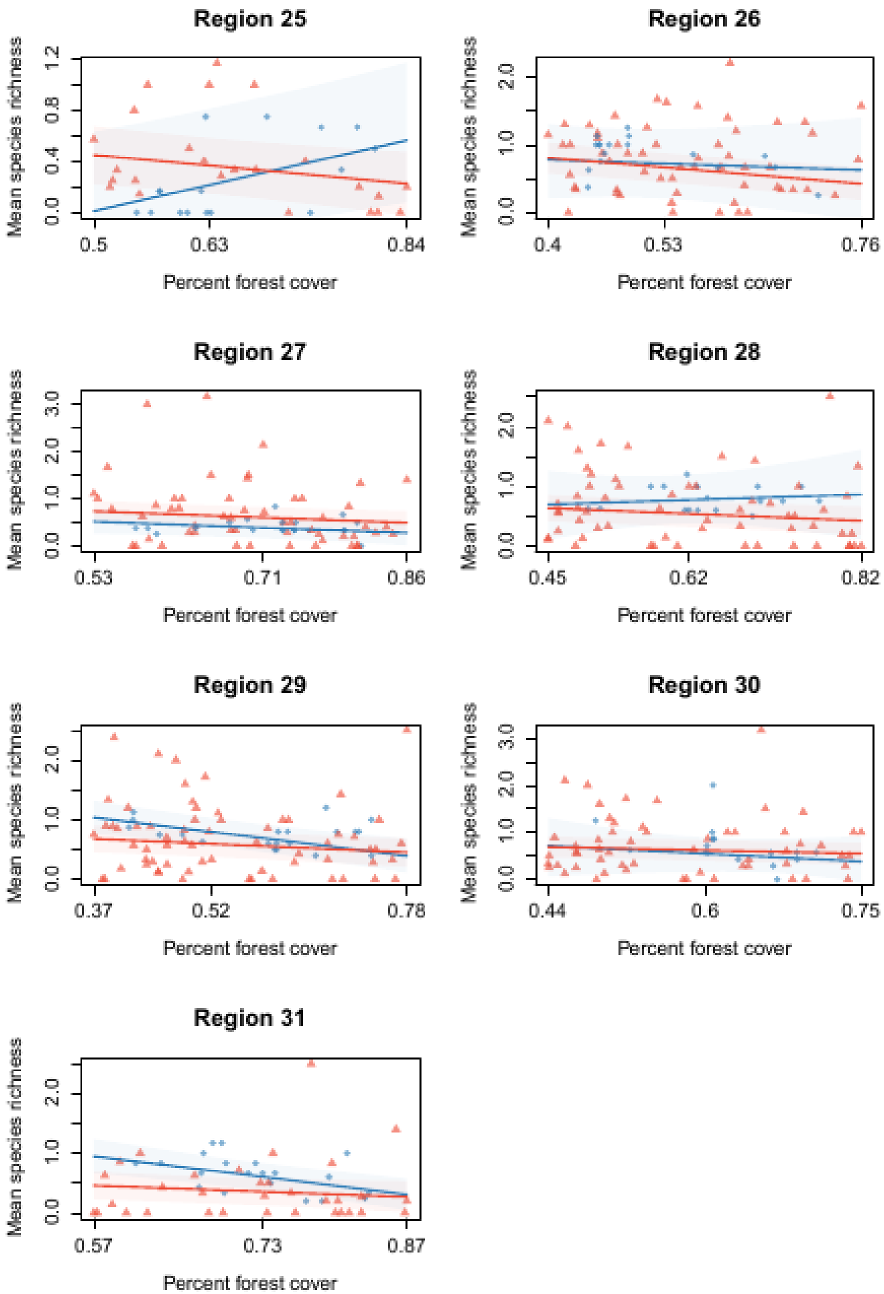
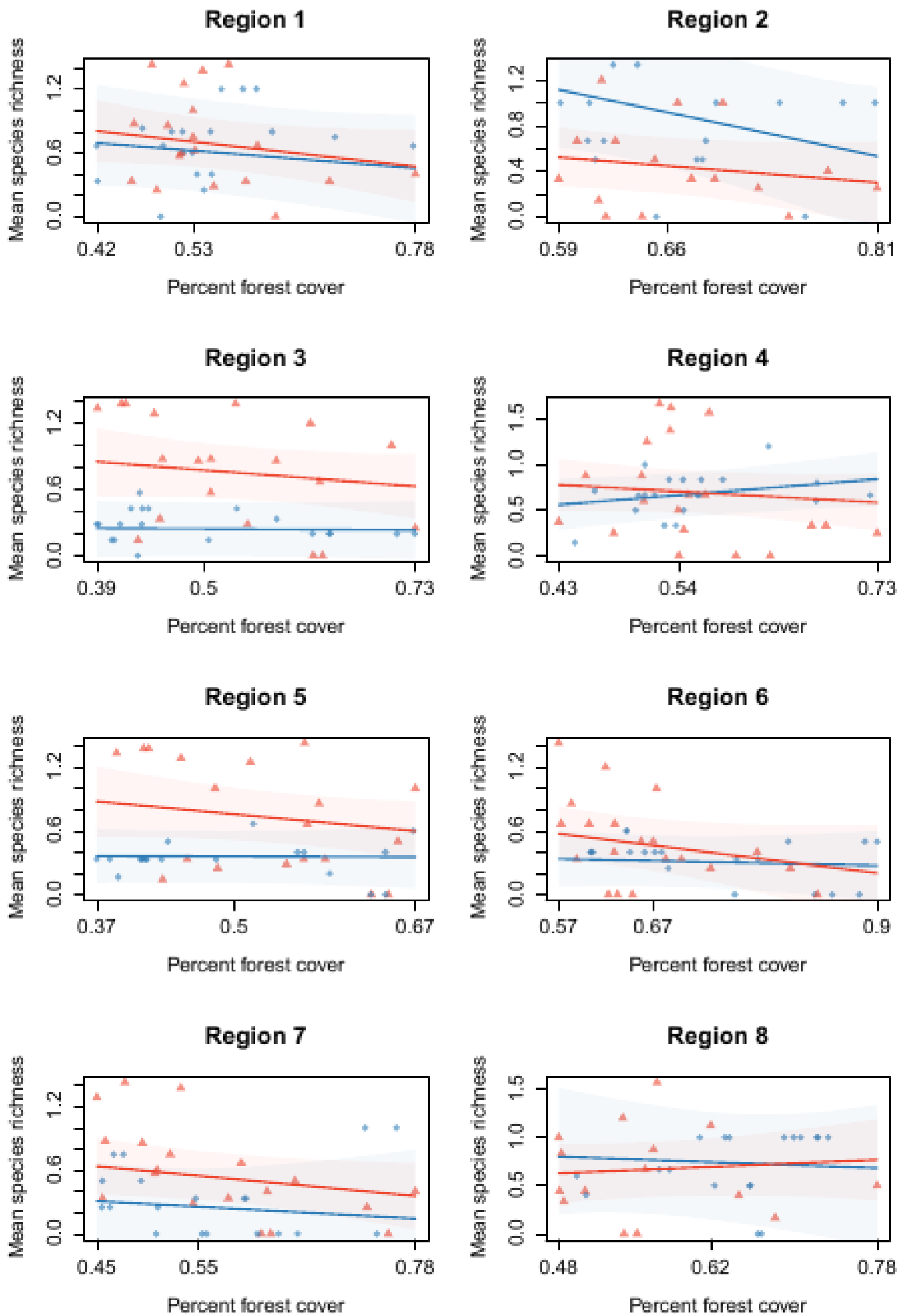


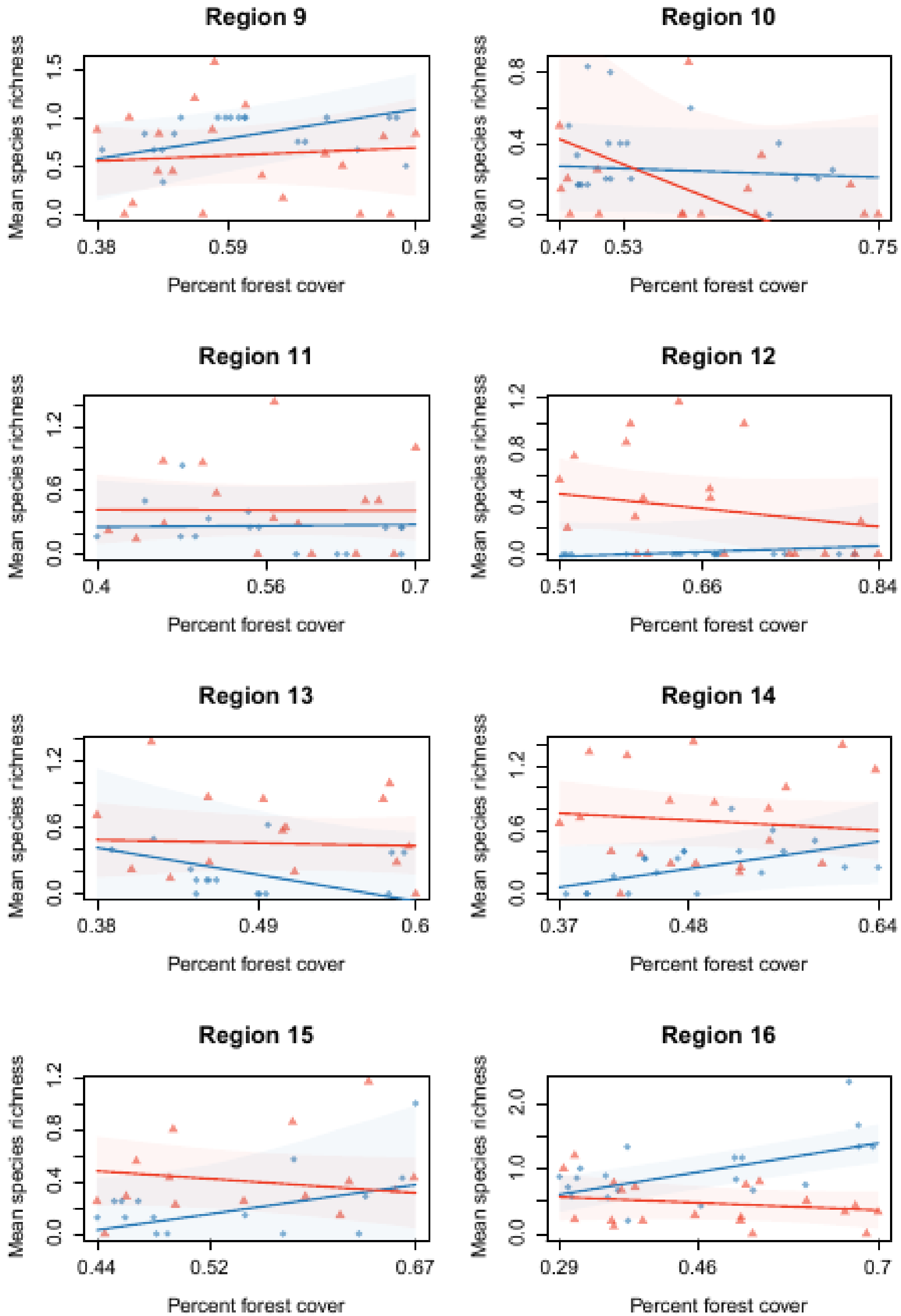
Figure E. Slope estimates (with 95% percentile interval shaded) measuring the effect of forest cover on open-habitat bird mean species richness over time at a temporal site from 2000 to 2019 (in blue) and in space across a set of neighbouring spatial sites in 2019 (in red) for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by the full number of available spatial sites within each space-time comparison, which may exceed the number of years informing the corresponding temporal slope.

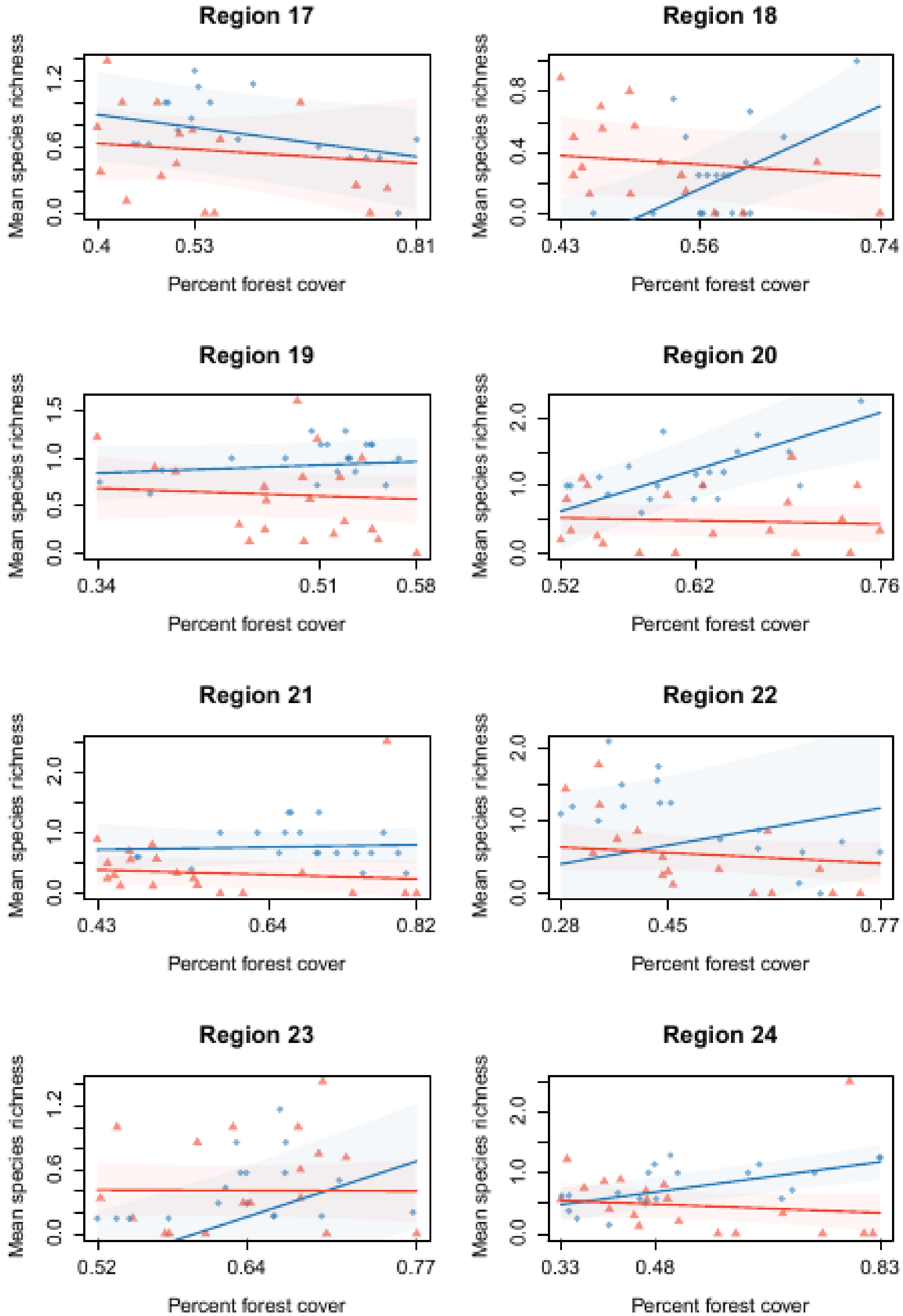
Table F. Slope parameter coefficient estimates measuring the effect of forest cover on open-habitat bird mean species richness over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope") for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by a subset number of eligible spatial sites equal to the number of years informing the corresponding temporal slope.

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
1	-0.07859	-0.26381	0.104401	-0.11063	-0.28779	0.065649
2	-0.30665	-0.69948	0.087299	-0.11665	-0.35245	0.119681
3	-0.00526	-0.08867	0.07705	-0.07847	-0.24449	0.084395
4	0.113836	-0.03165	0.277546	-0.0788	-0.26184	0.108499
5	-0.0047	-0.12508	0.110933	-0.11137	-0.29485	0.07183
6	-0.02183	-0.16642	0.118151	-0.13045	-0.32763	0.064451
7	-0.06024	-0.30992	0.238551	-0.10252	-0.26107	0.052527
8	-0.04751	-0.45391	0.398721	0.055869	-0.16107	0.269767
9	0.118163	-0.00481	0.243437	0.031631	-0.15218	0.211997
10	-0.02668	-0.14776	0.092195	-0.30141	-0.89982	0.319849
11	0.009106	-0.20048	0.204498	-0.00393	-0.18449	0.182203
12	0.029665	-0.11829	0.174419	-0.09059	-0.27692	0.095
13	-0.26275	-0.83075	0.304411	-0.02983	-0.26091	0.208737
14	0.187733	-0.08646	0.459355	-0.07036	-0.24944	0.111142
15	0.180134	-0.25121	0.574358	-0.08725	-0.26757	0.090081
16	0.228095	0.132375	0.317733	-0.05829	-0.20967	0.092909
17	-0.10944	-0.24906	0.025472	-0.05193	-0.30035	0.196406
18	0.367191	0.09924	0.651015	-0.05104	-0.19094	0.087821
19	0.06215	-0.0973	0.220513	-0.06004	-0.27264	0.146058
20	0.707267	0.23853	1.143003	-0.04463	-0.18822	0.097594
21	0.024278	-0.18038	0.172102	-0.04539	-0.16162	0.068431
22	0.189445	-0.04191	0.41735	-0.0554	-0.1756	0.065609
23	0.479724	0.244495	0.710159	-0.0053	-0.17505	0.165694

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
24	0.169383	0.089319	0.242648	-0.04858	-0.16014	0.061969
25	0.210916	0.046572	0.368582	-0.07816	-0.24751	0.090418
26	-0.04997	-0.4094	0.355935	-0.05628	-0.34974	0.244815
27	-0.04608	-0.18688	0.0951	-0.06185	-0.2595	0.136221
28	0.068732	-0.39755	0.533761	-0.03089	-0.20906	0.157651
29	-0.13607	-0.25641	-0.01299	-0.04057	-0.17166	0.093068
30	-0.12518	-0.56303	0.303218	-0.03633	-0.2187	0.153209
31	-0.27233	-0.45173	-0.10743	-0.09442	-0.29193	0.10501


Region 1
Mean species richness
0.0
0.6
1.2
0.42
0.53
0.78
Percent forest cover
Region 2
Mean species richness
0.0
0.4
0.8
1.2
0.59
0.66
0.81
Percent forest cover
Region 3
Mean species richness
0.0
0.6
1.2
0.39
0.5
0.73
Percent forest cover
Region 4
Mean species richness
0.0
0.5
1.0
1.5
0.43
0.54
0.73
Percent forest cover
Region 5
Mean species richness
0.0
0.6
1.2
0.37
0.5
0.67
Percent forest cover
Region 6
Mean species richness
0.0
0.6
1.2
0.57
0.67
0.9
Percent forest cover
Region 7
Mean species richness
0.0
0.6
1.2
0.45
0.55
0.78
Percent forest cover
Region 8
Mean species richness
0.0
0.5
1.0
1.5
0.48
0.62
0.78
Percent forest cover


Region 9
Mean species richness
0.0
0.5
1.0
1.5
0.38
0.59
0.9
Percent forest cover
Region 10
Mean species richness
0.0
0.4
0.8
0.47
0.53
0.75
Percent forest cover
Region 11
Mean species richness
0.0
0.6
1.2
0.4
0.56
0.7
Percent forest cover
Region 12
Mean species richness
0.0
0.4
0.8
1.2
0.51
0.66
0.84
Percent forest cover
Region 13
Mean species richness
0.0
0.6
1.2
0.38
0.49
0.6
Percent forest cover
Region 14
Mean species richness
0.0
0.6
1.2
0.37
0.48
0.64
Percent forest cover
Region 15
Mean species richness
0.0
0.4
0.8
1.2
0.44
0.52
0.67
Percent forest cover
Region 16
Mean species richness
0.0
1.0
2.0
0.29
0.46
0.7
Percent forest cover


Region 17
Mean species richness
0.0
0.6
1.2
0.4
0.53
0.81
Percent forest cover
Region 18
Mean species richness
0.0
0.4
0.8
0.43
0.56
0.74
Percent forest cover
Region 19
Mean species richness
0.0
0.5
1.0
1.5
0.34
0.51
0.58
Percent forest cover
Region 20
Mean species richness
0.0
1.0
2.0
0.52
0.62
0.76
Percent forest cover
Region 21
Mean species richness
0.0
1.0
2.0
0.43
0.64
0.82
Percent forest cover
Region 22
Mean species richness
0.0
1.0
2.0
0.28
0.45
0.77
Percent forest cover
Region 23
Mean species richness
0.0
0.6
1.2
0.52
0.64
0.77
Percent forest cover
Region 24
Mean species richness
0.0
1.0
2.0
0.33
0.48
0.83
Percent forest cover

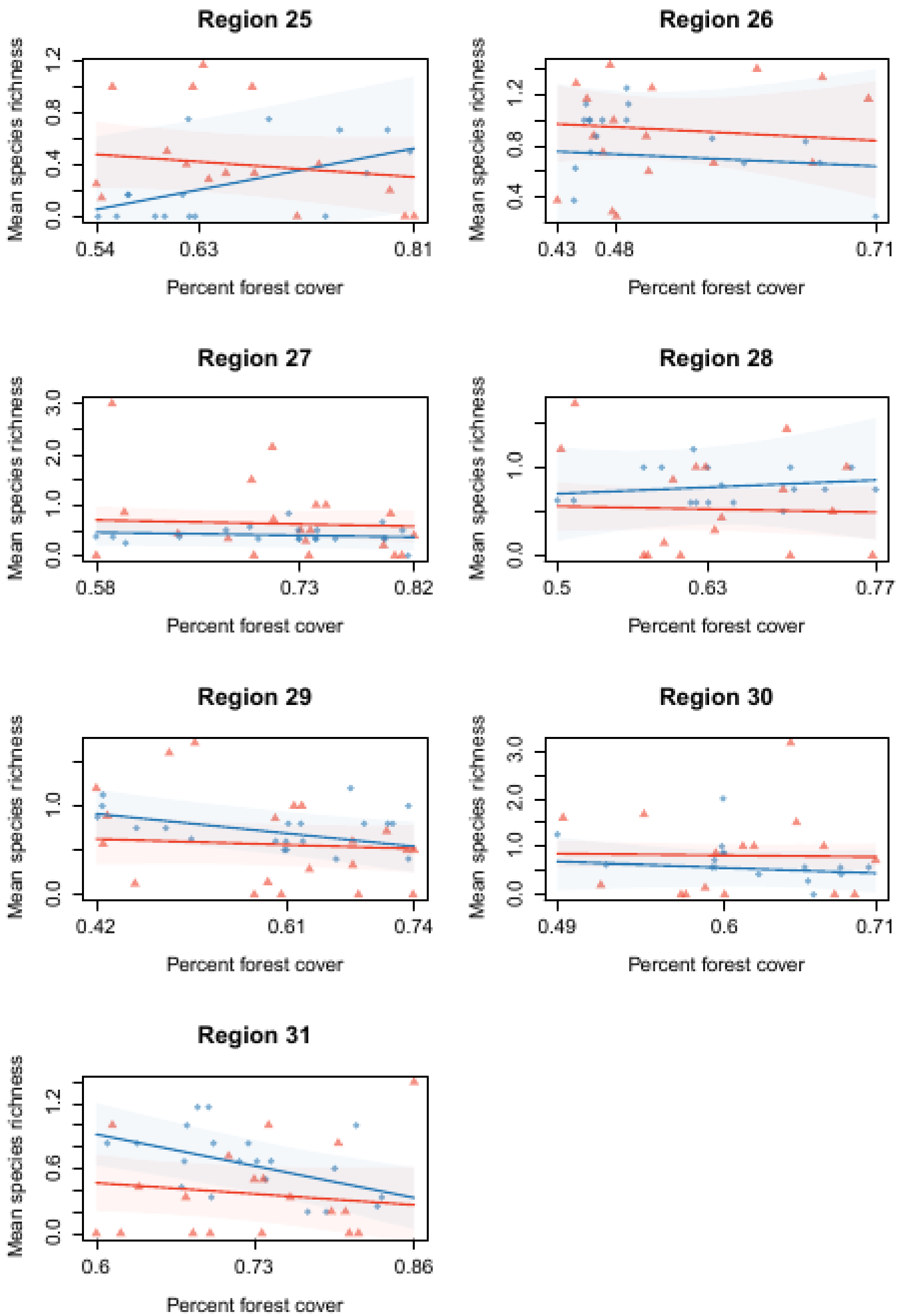
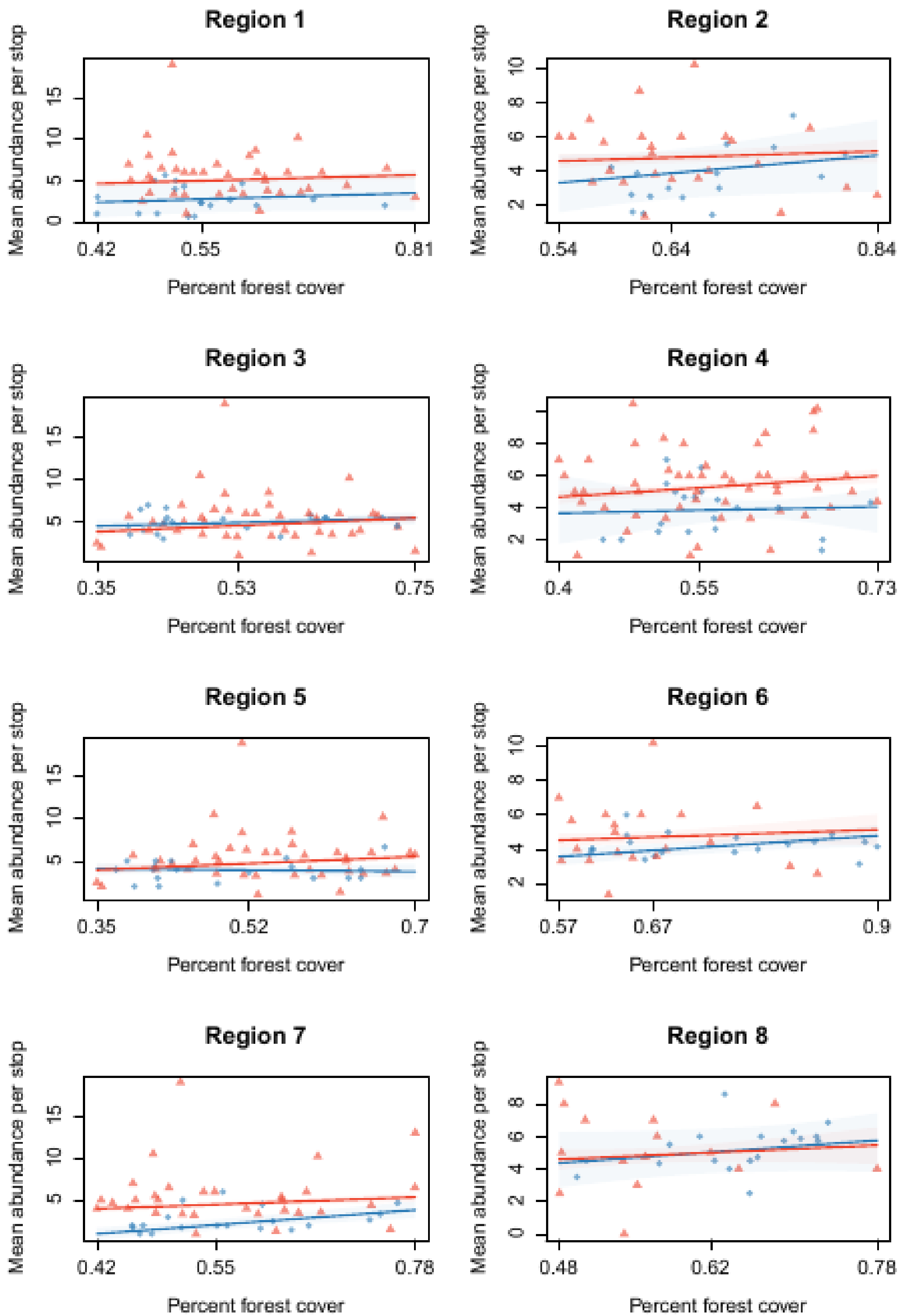


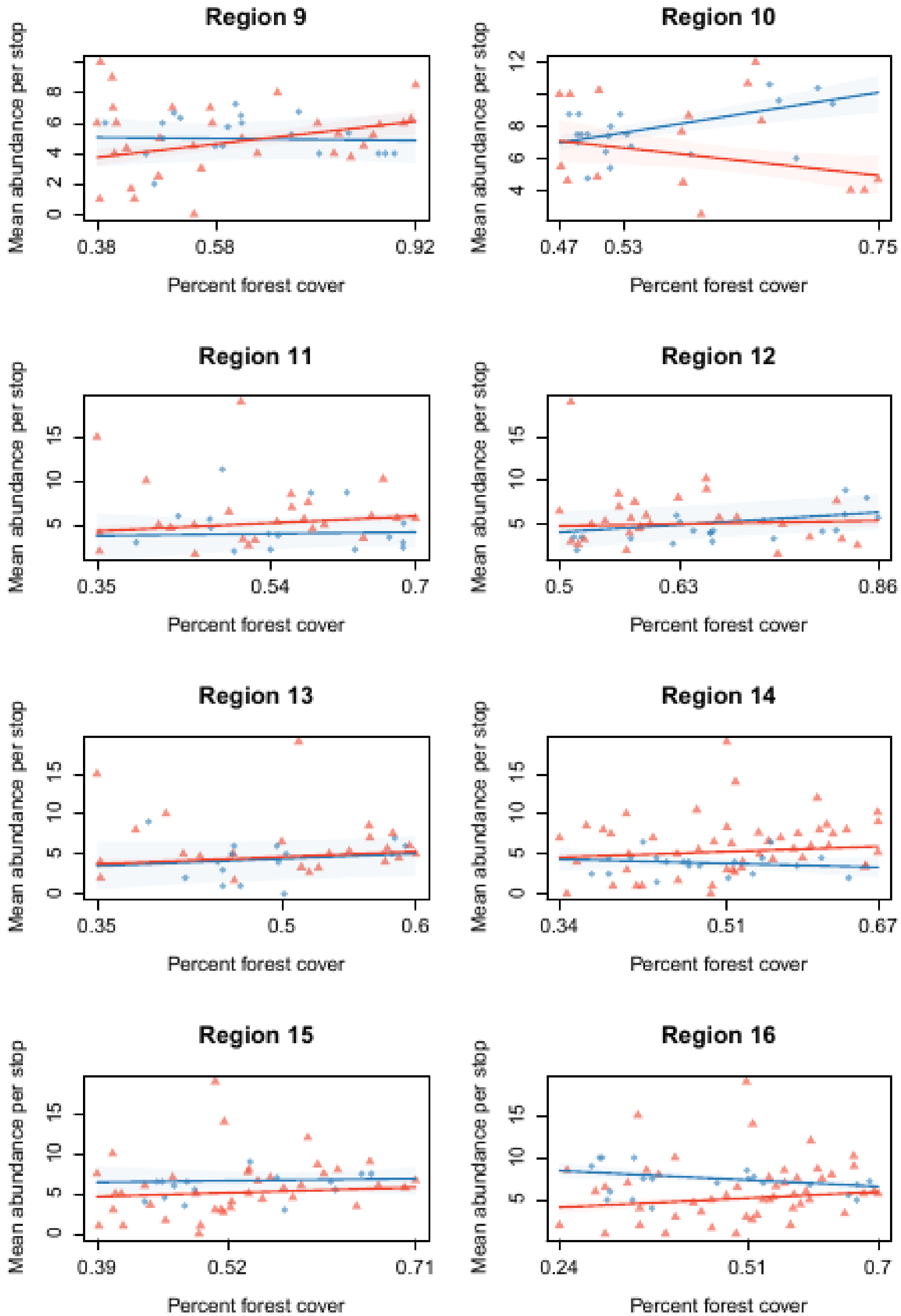
Figure F. Slope estimates (with 95% percentile interval shaded) measuring the effect of forest cover on open-habitat bird mean species richness over time at a temporal site from 2000 to 2019 (in blue) and in space across a set of neighbouring spatial sites in 2019 (in red) for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by a subset number of eligible spatial sites equal to the number of years informing the corresponding temporal slope.

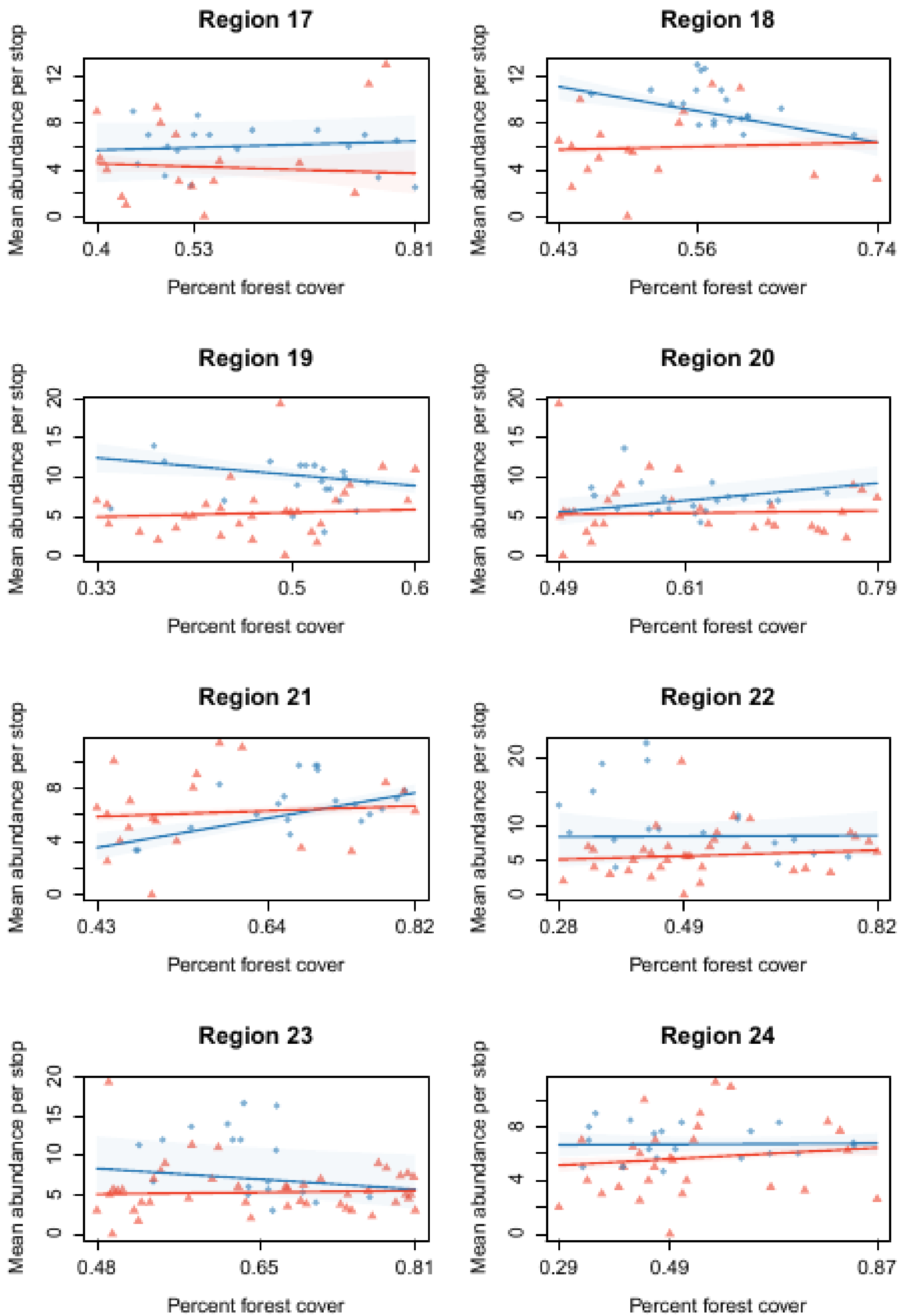
Table G. Slope parameter coefficient estimates measuring the effect of forest cover on forest bird mean abundance over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope") for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by the full number of available spatial sites within each space-time comparison, which may exceed the number of years informing the corresponding temporal slope.

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
1	0.34466	-0.35222	1.102633	0.330187	0.004786	0.647001
2	0.6467	-0.42671	1.782249	0.23066	-0.18814	0.650064
3	0.295982	-0.17062	0.755055	0.499448	0.186159	0.814115
4	0.154276	-1.68602	1.419535	0.496417	0.181741	0.802169
5	-0.12731	-0.65678	0.443705	0.545315	0.207604	0.875937
6	0.440945	0.042039	0.822366	0.225007	-0.26442	0.712496
7	0.95912	0.468545	1.446037	0.461805	0.124643	0.796727
8	0.567974	-0.50935	1.673616	0.35657	-0.37922	1.081811
9	-0.04409	-0.5843	0.539919	0.536943	0.199667	0.850311
10	1.375108	0.442674	2.031231	-0.9419	-1.98301	0.099542
11	0.141247	-1.18897	1.532197	0.598528	0.200413	0.975163
12	0.755844	0.325334	1.228959	0.207137	-0.2116	0.623795
13	0.760263	-0.71437	2.268953	0.769753	0.297035	1.256801
14	-0.37092	-1.37608	0.816394	0.501408	0.185097	0.810426
15	0.162028	-1.23396	1.478096	0.436085	0.10117	0.77364
16	-0.49596	-0.97201	-0.04329	0.481406	0.172184	0.784086
17	0.228436	-0.5118	0.862208	-0.2474	-1.06807	0.666897
18	-1.87111	-2.84693	-0.87447	0.249767	-0.14146	0.647886
19	-1.6015	-2.78694	-0.24525	0.419555	0.025041	0.81853
20	1.476741	0.560228	2.269328	0.190253	-0.08855	0.46753
21	1.285957	0.643015	1.759922	0.252107	-0.01239	0.523898
22	0.054558	-1.57088	1.150828	0.30034	0.069098	0.533363

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
23	-0.9794	-2.06921	0.047091	0.172859	-0.07057	0.407975
24	0.022781	-0.34795	0.377304	0.277129	0.038608	0.529014
25	-0.27869	-0.94025	0.451176	0.162071	-0.22286	0.518308
26	-1.19913	-2.41915	-0.05021	0.442384	0.11355	0.776013
27	-0.65183	-1.39956	0.129362	0.102392	-0.20167	0.3925
28	0.15688	-0.96276	1.305674	0.213403	0.006358	0.421556
29	0.97747	0.541215	1.439544	0.248135	0.047179	0.452509
30	-1.59092	-2.90076	-0.15983	0.241056	-0.00365	0.487593
31	2.272576	1.170349	3.569141	0.072935	-0.28512	0.429642


Region 1
Mean abundance per stop
0
5
10
15
0.42
0.55
0.81
Percent forest cover
Region 2
Mean abundance per stop
2
4
6
8
10
0.54
0.64
0.84
Percent forest cover
Region 3
Mean abundance per stop
5
10
15
0.35
0.53
0.75
Percent forest cover
Region 4
Mean abundance per stop
2
4
6
8
0.4
0.55
0.73
Percent forest cover
Region 5
Mean abundance per stop
5
10
15
0.35
0.52
0.7
Percent forest cover
Region 6
Mean abundance per stop
2
4
6
8
10
0.57
0.67
0.9
Percent forest cover
Region 7
Mean abundance per stop
5
10
15
0.42
0.55
0.78
Percent forest cover
Region 8
Mean abundance per stop
0
2
4
6
8
0.48
0.62
0.78
Percent forest cover


Region 9
Mean abundance per stop
0
2
4
6
8
0.38
0.58
0.92
Percent forest cover
Region 10
Mean abundance per stop
4
6
8
12
0.47
0.53
0.75
Percent forest cover
Region 11
Mean abundance per stop
5
10
15
0.35
0.54
0.7
Percent forest cover
Region 12
Mean abundance per stop
5
10
15
0.5
0.63
0.86
Percent forest cover
Region 13
Mean abundance per stop
0
5
10
15
0.35
0.5
0.6
Percent forest cover
Region 14
Mean abundance per stop
0
5
10
15
0.34
0.51
0.67
Percent forest cover
Region 15
Mean abundance per stop
0
5
10
15
0.39
0.52
0.71
Percent forest cover
Region 16
Mean abundance per stop
5
10
15
0.24
0.51
0.7
Percent forest cover


Region 17
Region 18
Region 19
Region 20
Region 21
Region 22
Region 23
Region 24
Mean abundance per stop
Percent forest cover
0.4
0.53
0.81
0.43
0.56
0.74
0.33
0.5
0.6
0.49
0.61
0.79
0.43
0.64
0.82
0.28
0.49
0.82
0.48
0.65
0.81
0.29
0.49
0.87

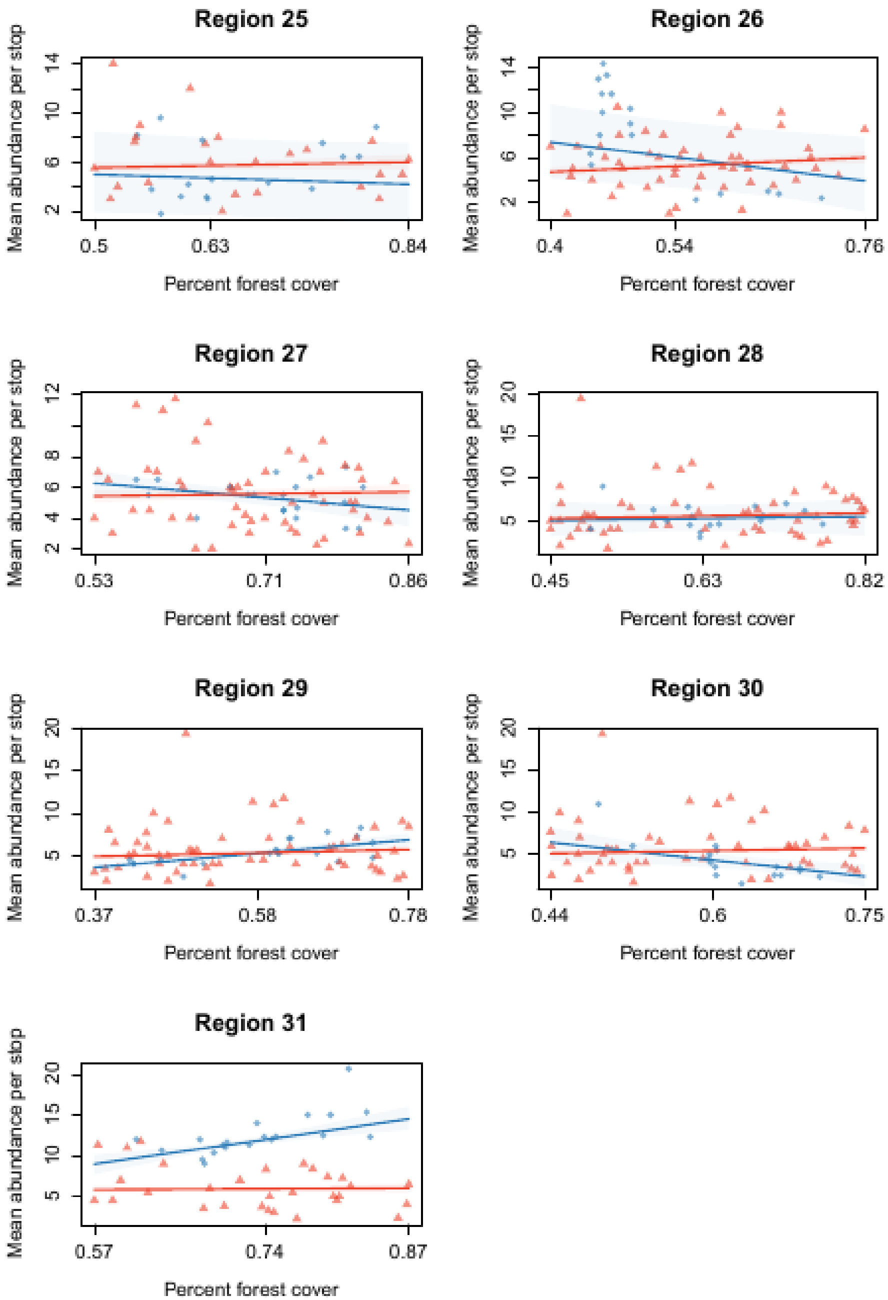
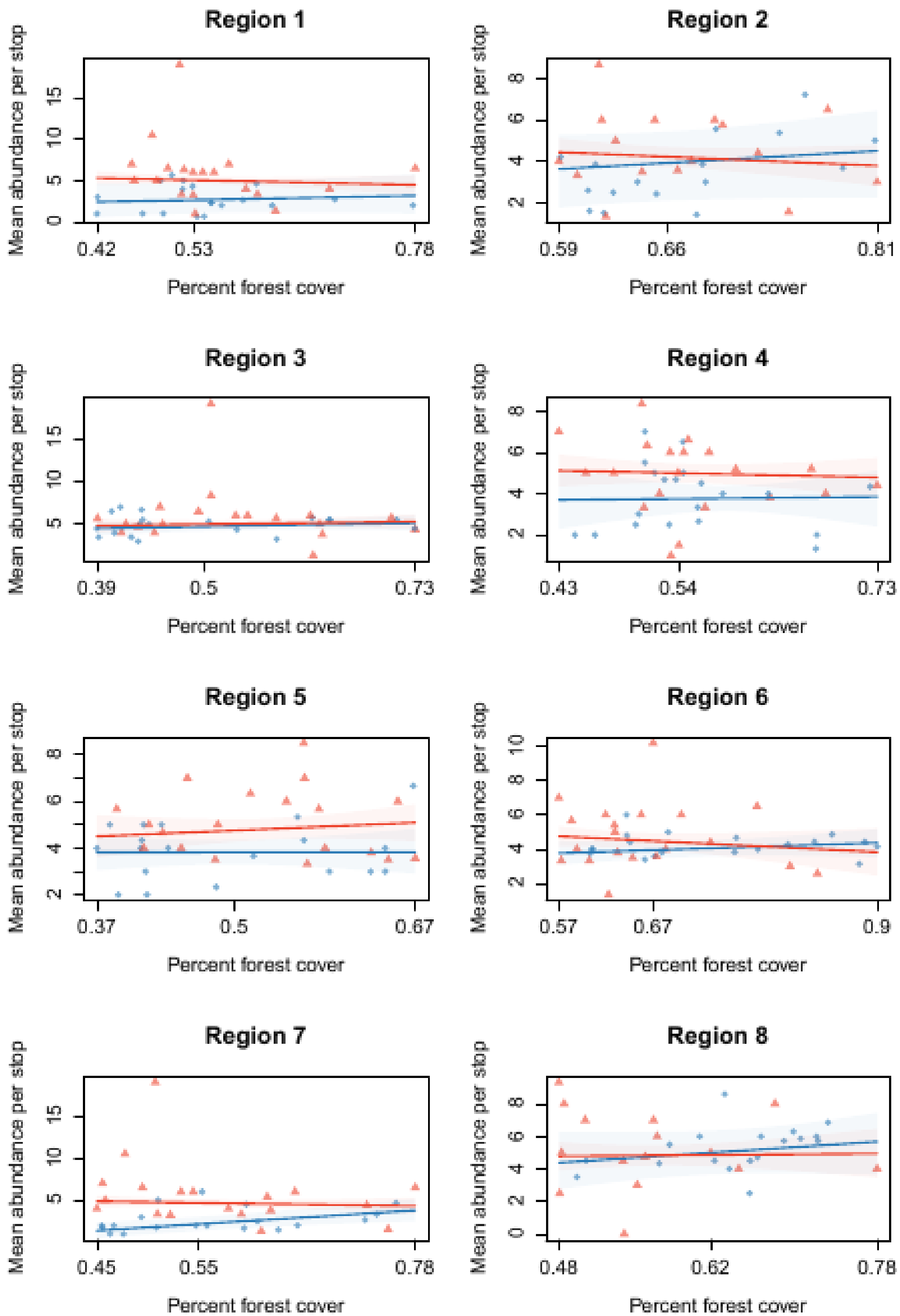


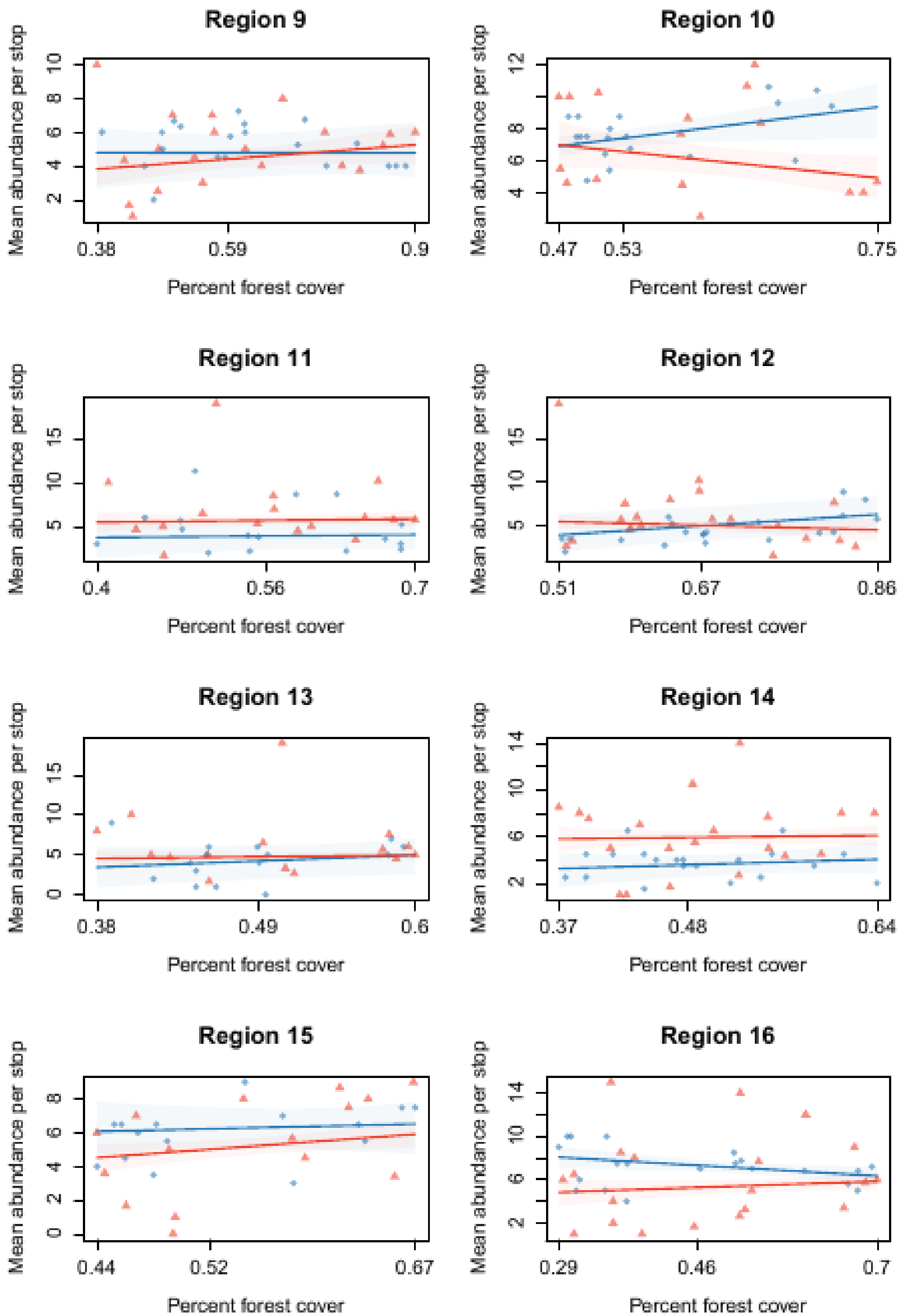
Figure G. Slope estimates (with 95% percentile interval shaded) measuring the effect of forest cover on forest bird mean abundance over time at a temporal site from 2000 to 2019 (in blue) and in space across a set of neighbouring spatial sites in 2019 (in red) for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by the full number of available spatial sites within each space-time comparison, which may exceed the number of years informing the corresponding temporal slope.

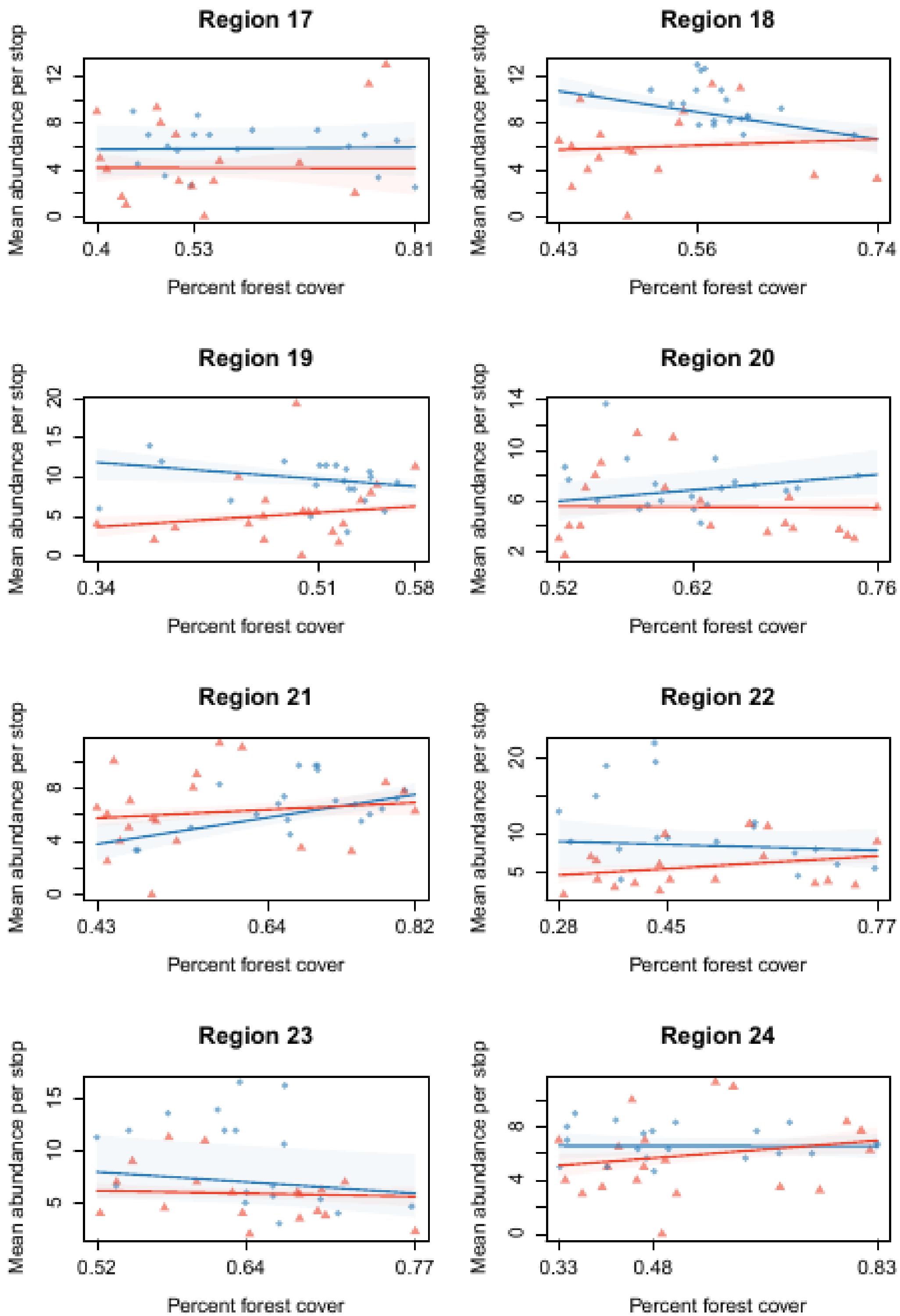
Table H. Slope parameter coefficient estimates measuring the effect of forest cover on forest bird mean abundance over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope") for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by a subset number of eligible spatial sites equal to the number of years informing the corresponding temporal slope.

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
1	0.24852	-0.59662	1.155697	-0.2769	-1.02944	0.4349
2	0.467303	-0.6527	1.598623	-0.34452	-1.19204	0.519556
3	0.232067	-0.35202	0.780539	0.170485	-0.42915	0.77931
4	0.062601	-1.2929	1.241977	-0.13908	-0.8799	0.611192
5	0.001065	-0.6325	0.705534	0.23536	-0.46816	0.932941
6	0.213744	-0.31884	0.730466	-0.32448	-1.04311	0.44043
7	0.879667	0.224575	1.519722	-0.19477	-0.82659	0.434426
8	0.518118	-0.7172	1.733113	0.067998	-0.90147	1.047098
9	-0.00545	-0.63758	0.64703	0.336261	-0.19342	0.853441
10	1.049696	-0.19557	1.927892	-0.88009	-1.98058	0.260126
11	0.118035	-1.17056	1.382854	0.148548	-0.70577	0.997113
12	0.79677	0.224077	1.387115	-0.33011	-1.06062	0.43225
13	0.854967	-0.63164	2.337422	0.246535	-0.62964	1.094499
14	0.351435	-0.85986	1.534428	0.13482	-0.71294	0.9568
15	0.237831	-1.13682	1.576543	0.731845	-0.12109	1.59628
16	-0.50514	-1.04288	0.085556	0.294328	-0.30951	0.951886
17	0.057878	-0.89097	0.882906	-0.01371	-1.09262	1.245913
18	-1.58246	-2.59222	-0.5194	0.344288	-0.2984	1.025027
19	-1.56409	-2.87333	0.147425	1.352958	0.252086	2.359249
20	1.032134	-0.15012	2.104546	-0.05525	-0.74384	0.645969
21	1.138147	0.332612	1.789446	0.356386	-0.14015	0.860434
22	-0.29121	-1.46171	0.801264	0.621431	0.122687	1.141799
23	-1.01751	-2.30049	0.312621	-0.28021	-1.13759	0.568973

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
24	-0.00839	-0.46862	0.44812	0.450552	-0.00326	0.931454
25	-0.02583	-0.93536	1.010978	-0.32675	-1.26193	0.632011
26	-1.53408	-2.81396	-0.29968	-0.03506	-1.04605	0.999681
27	-0.51984	-1.32538	0.323701	-0.16896	-0.91443	0.566979
28	-0.00763	-1.23096	1.22286	-0.15706	-0.9856	0.67947
29	0.996996	0.420373	1.572369	0.231235	-0.33445	0.780958
30	-1.30696	-2.7829	0.246565	-0.02177	-1.17979	1.105217
31	2.330649	1.19308	3.518722	-0.51358	-1.3408	0.304392


Region 1
Region 2
Region 3
Region 4
Region 5
Region 6
Region 7
Region 8
Mean abundance per stop
Percent forest cover
0.42
0.53
0.78
0.59
0.66
0.81
0.39
0.5
0.73
0.43
0.54
0.73
0.37
0.5
0.67
0.57
0.67
0.9
0.45
0.55
0.78
0.48
0.62
0.78


Region 9
Mean abundance per stop
2 4 6 8 10
0.38 0.59 0.9
Percent forest cover
Region 10
Mean abundance per stop
4 6 8 12
0.47 0.53 0.75
Percent forest cover
Region 11
Mean abundance per stop
5 10 15
0.4 0.56 0.7
Percent forest cover
Region 12
Mean abundance per stop
5 10 15
0.51 0.67 0.86
Percent forest cover
Region 13
Mean abundance per stop
0 5 10 15
0.38 0.49 0.6
Percent forest cover
Region 14
Mean abundance per stop
2 6 10 14
0.37 0.48 0.64
Percent forest cover
Region 15
Mean abundance per stop
0 2 4 6 8
0.44 0.52 0.67
Percent forest cover
Region 16
Mean abundance per stop
2 6 10 14
0.29 0.46 0.7
Percent forest cover


Region 17
Mean abundance per stop
0 4 8 12
0.4 0.53 0.81
Percent forest cover
Region 18
Mean abundance per stop
0 4 8 12
0.43 0.56 0.74
Percent forest cover
Region 19
Mean abundance per stop
0 5 10 15 20
0.34 0.51 0.58
Percent forest cover
Region 20
Mean abundance per stop
2 6 10 14
0.52 0.62 0.76
Percent forest cover
Region 21
Mean abundance per stop
0 4 8
0.43 0.64 0.82
Percent forest cover
Region 22
Mean abundance per stop
5 10 20
0.28 0.45 0.77
Percent forest cover
Region 23
Mean abundance per stop
5 10 15
0.52 0.64 0.77
Percent forest cover
Region 24
Mean abundance per stop
0 4 8
0.33 0.48 0.83
Percent forest cover

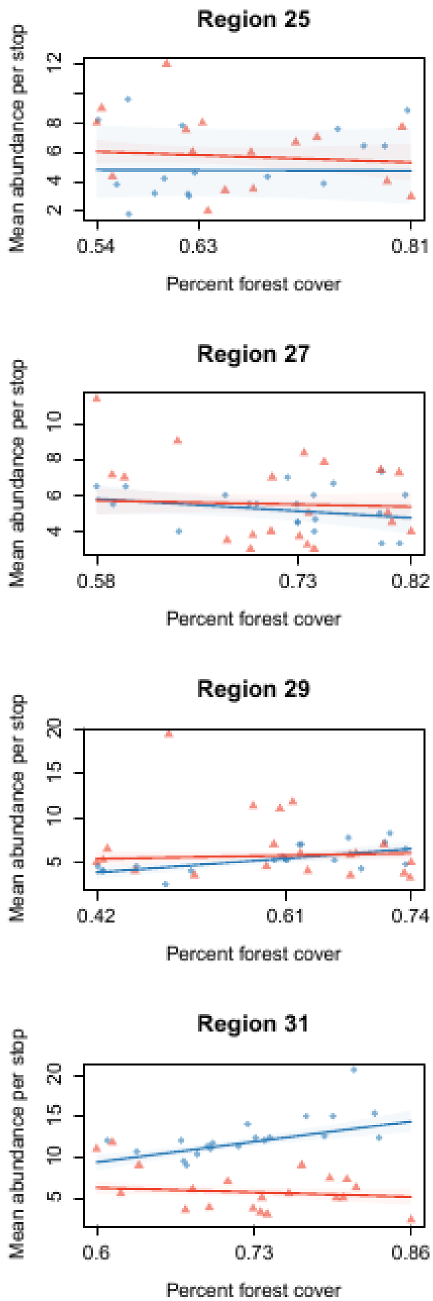
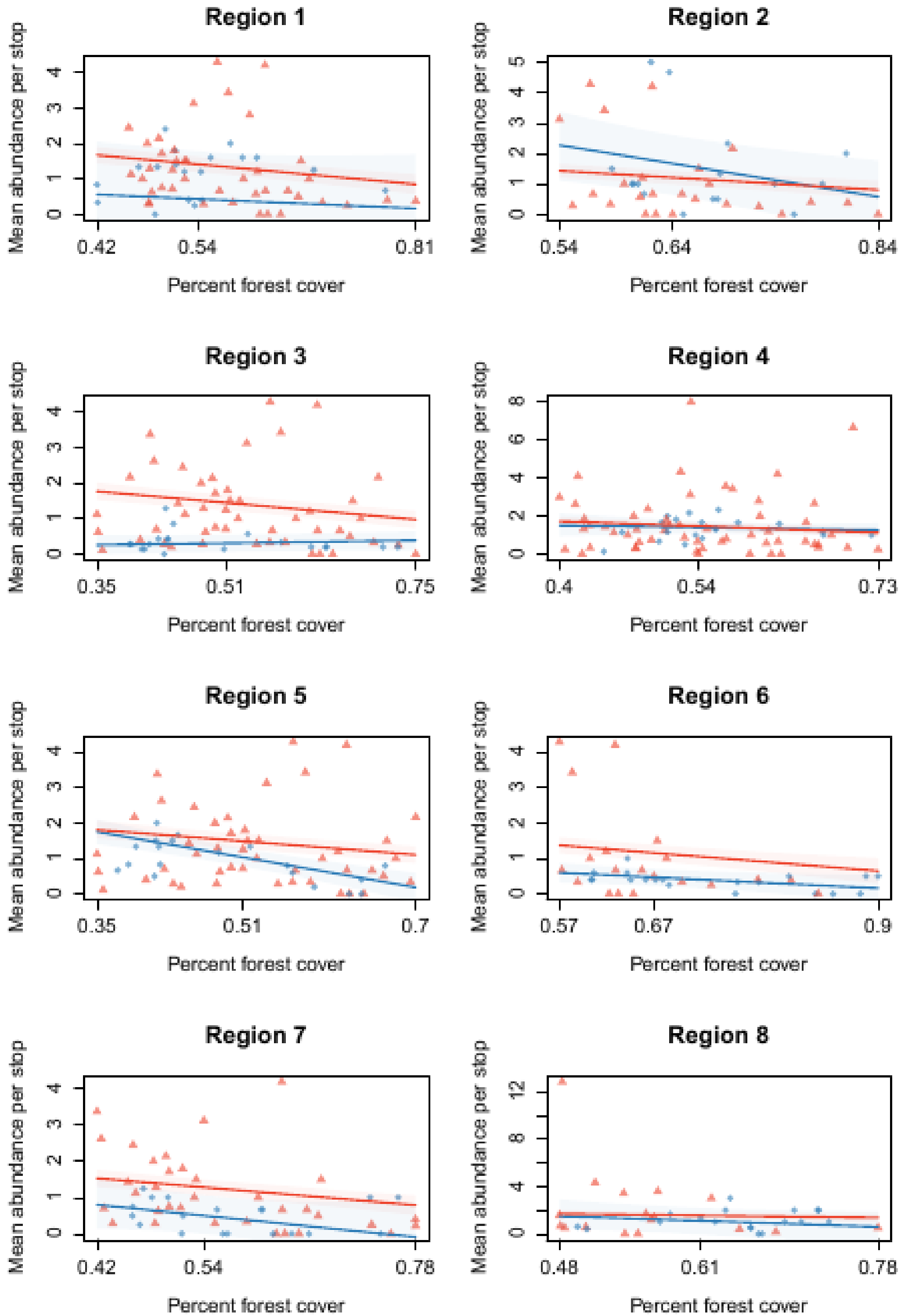


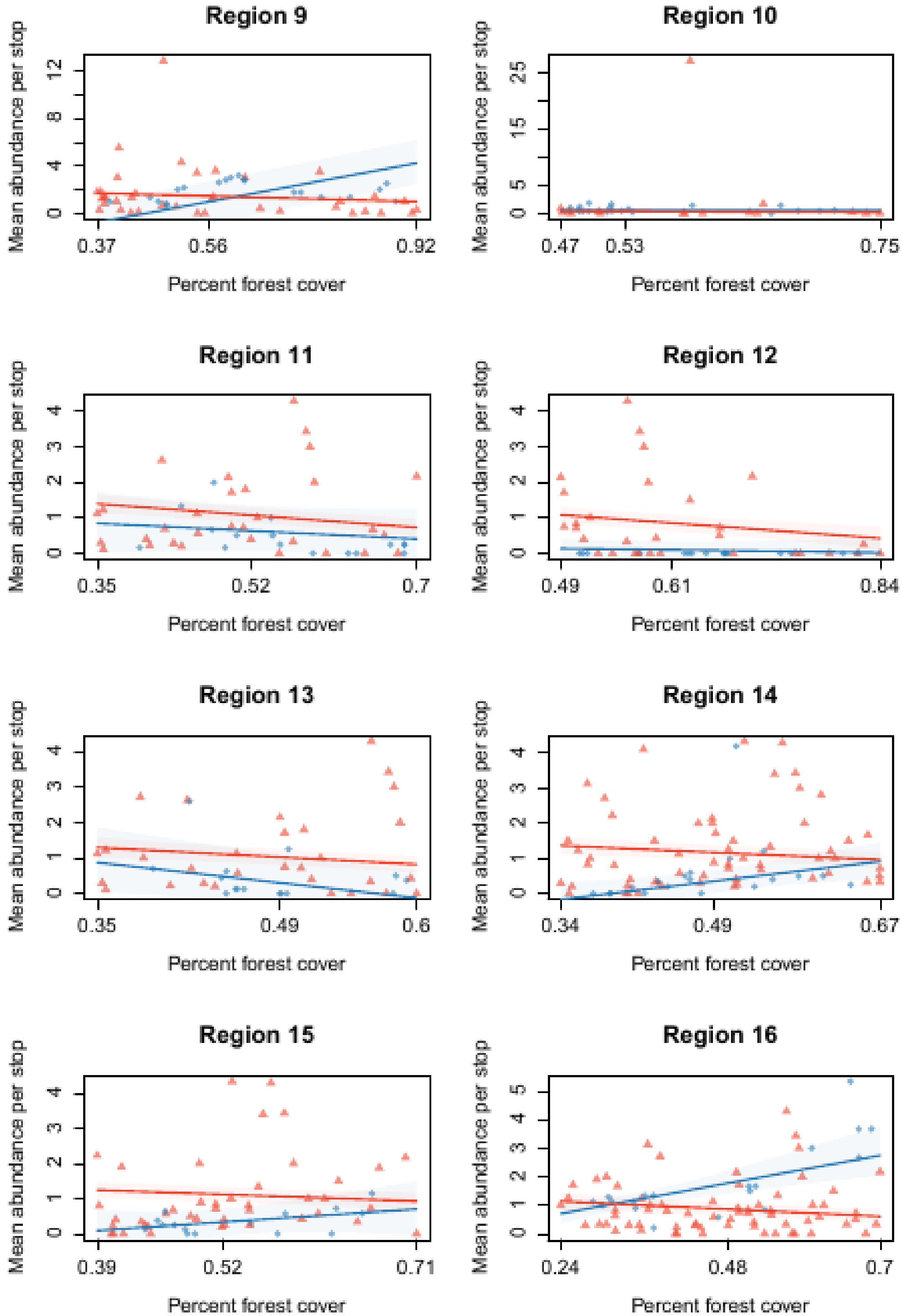
Figure H. Slope estimates (with 95% percentile interval shaded) measuring the effect of forest cover on forest bird mean abundance over time at a temporal site from 2000 to 2019 (in blue) and in space across a set of neighbouring spatial sites in 2019 (in red) for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by a subset number of eligible spatial sites equal to the number of years informing the corresponding temporal slope.

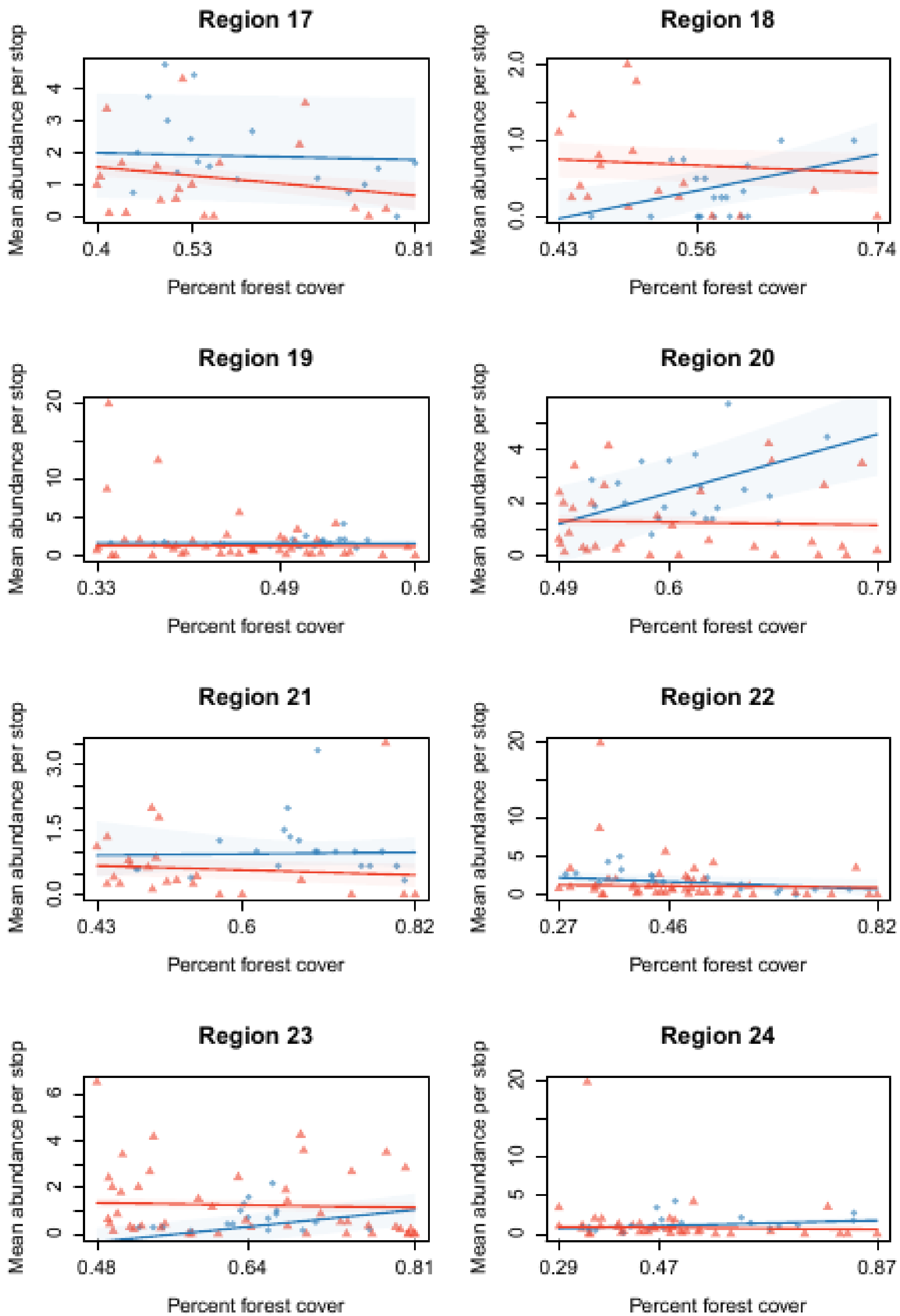
Table I. Slope parameter coefficient estimates measuring the effect of forest cover on open-habitat bird mean abundance over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope") for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by the full number of available spatial sites within each space-time comparison, which may exceed the number of years informing the corresponding temporal slope.

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
1	-0.12489	-0.49668	0.262553	-0.26039	-0.37045	-0.15536
2	-0.6987	-1.26447	-0.01309	-0.25914	-0.39886	-0.12672
3	0.039783	-0.057	0.137102	-0.24835	-0.34561	-0.15348
4	-0.09808	-0.45329	0.271766	-0.23068	-0.3377	-0.12685
5	-0.5537	-0.79847	-0.31257	-0.24826	-0.34821	-0.14903
6	-0.16275	-0.36546	0.030395	-0.26721	-0.42378	-0.11824
7	-0.30858	-0.73256	0.119914	-0.25652	-0.36699	-0.14901
8	-0.3767	-1.0796	0.525262	-0.14133	-0.35298	0.060504
9	1.137556	0.914821	1.367891	-0.15903	-0.27399	-0.06505
10	0.019634	-0.16224	0.185716	-0.09722	-0.72624	0.551655
11	-0.15543	-0.55692	0.166888	-0.23658	-0.35891	-0.11174
12	-0.04237	-0.23076	0.155463	-0.23754	-0.37282	-0.10474
13	-0.49315	-1.14798	0.140064	-0.23422	-0.39693	-0.0658
14	0.411379	-0.00042	0.761265	-0.1522	-0.2588	-0.05207
15	0.236046	-0.36148	0.767288	-0.12448	-0.23252	-0.02312
16	0.548637	0.278996	0.928576	-0.14088	-0.25319	-0.03088
17	-0.06468	-0.3187	0.205385	-0.27076	-0.4594	-0.08976
18	0.338245	0.036183	0.6838	-0.07244	-0.18855	0.044567
19	-0.03615	-0.33013	0.281643	-0.05742	-0.16337	0.050215
20	1.382794	0.683159	2.07279	-0.07104	-0.15442	0.0115
21	0.020573	-0.38032	0.243066	-0.07028	-0.1586	0.020812
22	-0.34659	-0.75729	0.038997	-0.07005	-0.14342	0.005073

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
23	0.521568	0.198529	0.803508	-0.077	-0.14758	-0.00787
24	0.227449	0.027403	0.378397	-0.07302	-0.14827	0.005838
25	0.375315	0.138899	0.583735	-0.07315	-0.17697	0.03024
26	0.176618	-1.8736	1.783403	-0.22072	-0.32876	-0.11103
27	0.217447	-0.41199	0.582962	-0.09232	-0.18587	-0.00229
28	-0.32421	-1.27013	0.485191	-0.0741	-0.14195	-0.00618
29	0.127394	-0.09035	0.337997	-0.0678	-0.13591	0.002354
30	-0.17842	-0.89337	0.566886	-0.06323	-0.13683	0.011266
31	-0.08752	-0.34755	0.124917	-0.08344	-0.18763	0.024732


Region 1
Mean abundance per stop
0 1 2 3 4
0.42 0.54 0.81
Percent forest cover
Region 2
Mean abundance per stop
0 1 2 3 4 5
0.54 0.64 0.84
Percent forest cover
Region 3
Mean abundance per stop
0 1 2 3 4
0.35 0.51 0.75
Percent forest cover
Region 4
Mean abundance per stop
0 2 4 6 8
0.4 0.54 0.73
Percent forest cover
Region 5
Mean abundance per stop
0 1 2 3 4
0.35 0.51 0.7
Percent forest cover
Region 6
Mean abundance per stop
0 1 2 3 4
0.57 0.67 0.9
Percent forest cover
Region 7
Mean abundance per stop
0 1 2 3 4
0.42 0.54 0.78
Percent forest cover
Region 8
Mean abundance per stop
0 4 8 12
0.48 0.61 0.78
Percent forest cover


Region 9
Mean abundance per stop
0
4
8
12
0.37
0.56
0.92
Percent forest cover
Region 10
Mean abundance per stop
0
5
15
25
0.47
0.53
0.75
Percent forest cover
Region 11
Mean abundance per stop
0
1
2
3
4
0.35
0.52
0.7
Percent forest cover
Region 12
Mean abundance per stop
0
1
2
3
4
0.49
0.61
0.84
Percent forest cover
Region 13
Mean abundance per stop
0
1
2
3
4
0.35
0.49
0.6
Percent forest cover
Region 14
Mean abundance per stop
0
1
2
3
4
0.34
0.49
0.67
Percent forest cover
Region 15
Mean abundance per stop
0
1
2
3
4
0.39
0.52
0.71
Percent forest cover
Region 16
Mean abundance per stop
0
1
2
3
4
5
0.24
0.48
0.7
Percent forest cover


Region 17
Mean abundance per stop
0
1
2
3
4
0.4
0.53
0.81
Percent forest cover
Region 18
Mean abundance per stop
0.0
1.0
2.0
0.43
0.56
0.74
Percent forest cover
Region 19
Mean abundance per stop
0
5
10
20
0.33
0.49
0.6
Percent forest cover
Region 20
Mean abundance per stop
0
2
4
0.49
0.6
0.79
Percent forest cover
Region 21
Mean abundance per stop
0.0
1.5
3.0
0.43
0.6
0.82
Percent forest cover
Region 22
Mean abundance per stop
0
5
10
20
0.27
0.46
0.82
Percent forest cover
Region 23
Mean abundance per stop
0
2
4
6
0.48
0.64
0.81
Percent forest cover
Region 24
Mean abundance per stop
0
5
10
20
0.29
0.47
0.87
Percent forest cover

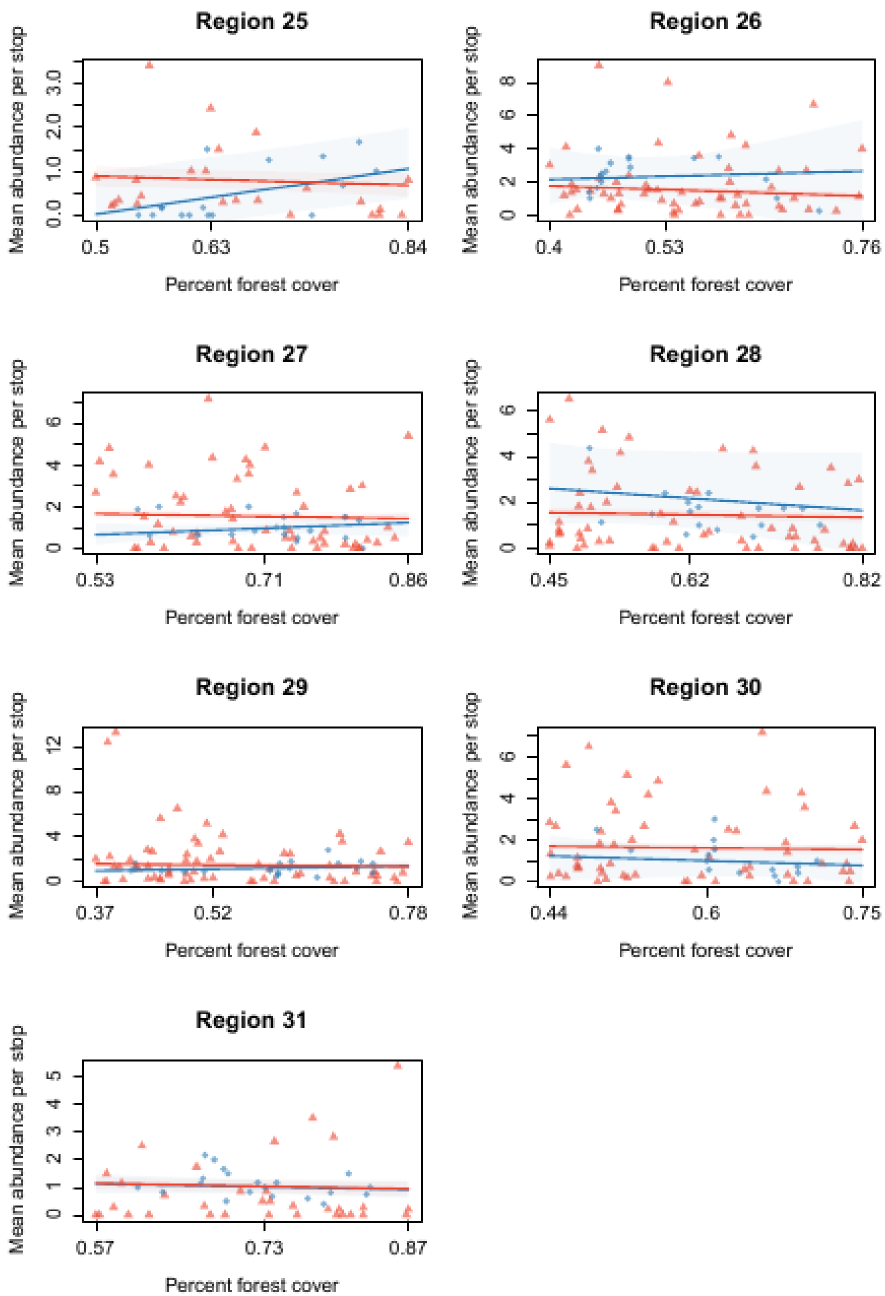
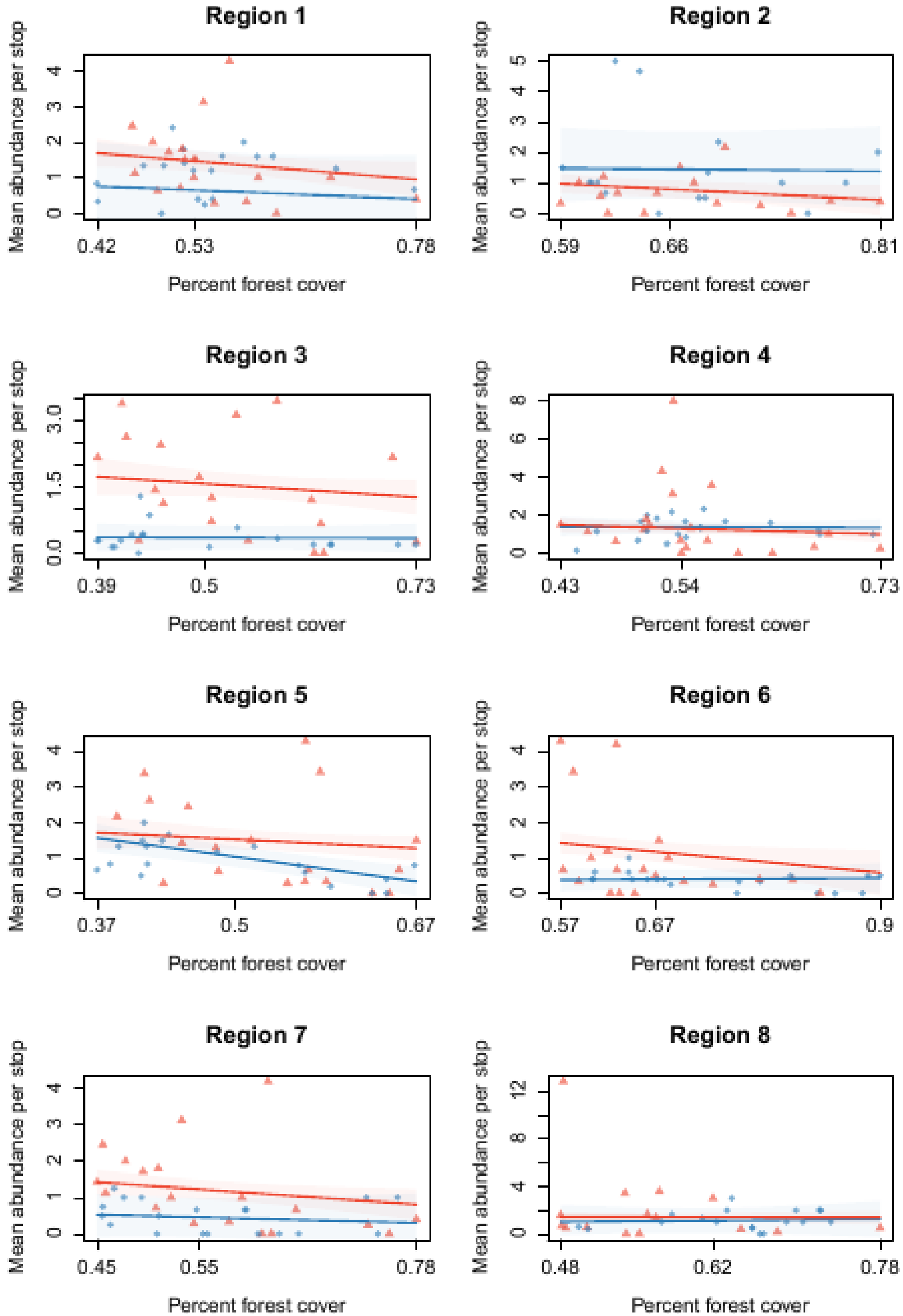


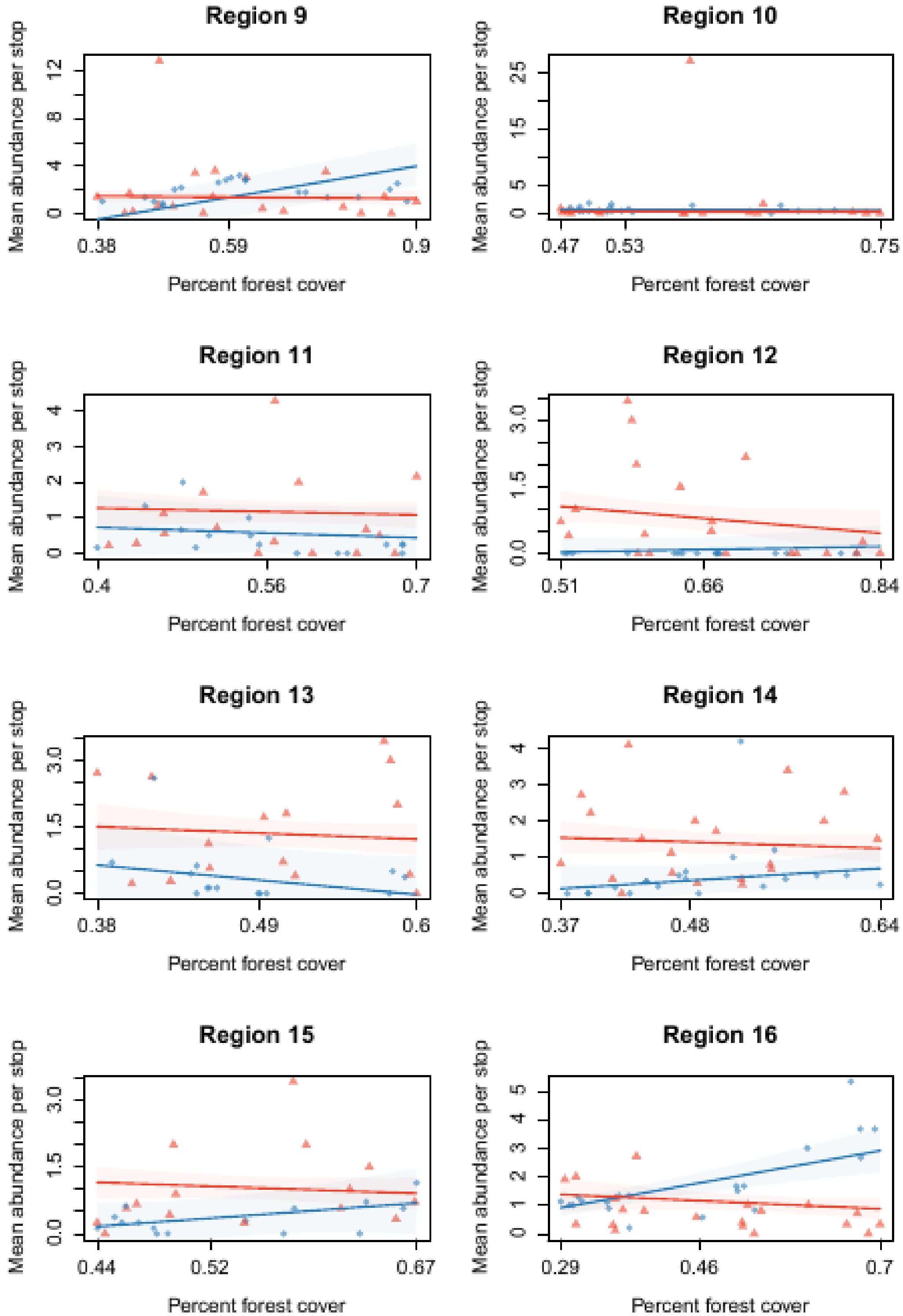
Figure I. Slope estimates (with 95% percentile interval shaded) measuring the effect of forest cover on open-habitat bird mean abundance over time at a temporal site from 2000 to 2019 (in blue) and in space across a set of neighbouring spatial sites in 2019 (in red) for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by the full number of available spatial sites within each space-time comparison, which may exceed the number of years informing the corresponding temporal slope.

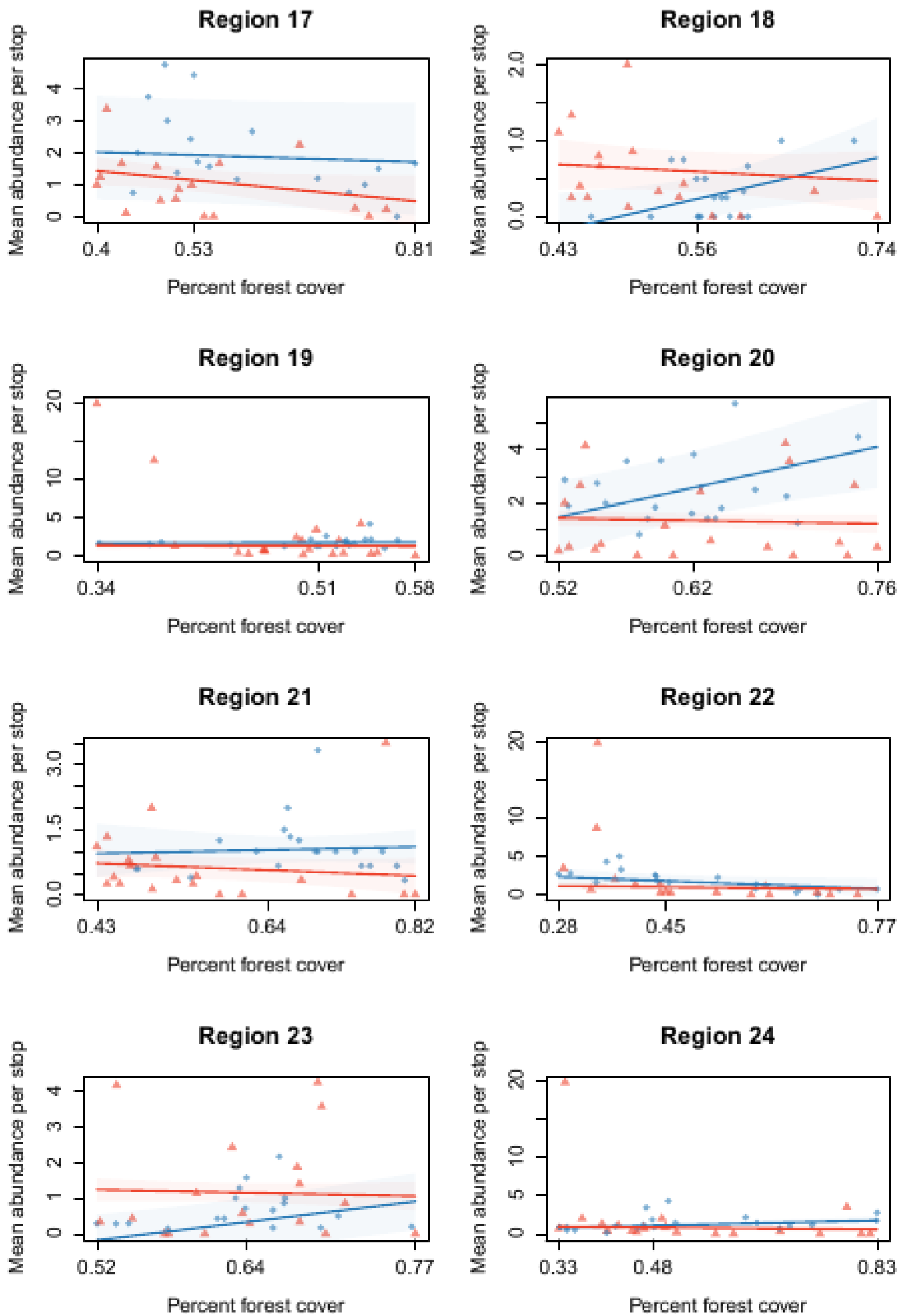
Table J. Slope parameter coefficient estimates measuring the effect of forest cover on open-habitat bird mean abundance over time at a temporal site from 2000 to 2019 ("temporal slope") and in space across a set of neighbouring spatial sites in 2019 ("spatial slope") for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by a subset number of eligible spatial sites equal to the number of years informing the corresponding temporal slope.

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
1	-0.11991	-0.46812	0.282393	-0.24673	-0.5348	0.043124
2	-0.05222	-0.84132	0.749778	-0.28035	-0.63952	0.082182
3	-0.006	-0.1573	0.142695	-0.16232	-0.43247	0.106625
4	-0.02839	-0.38426	0.343304	-0.19444	-0.49485	0.109722
5	-0.49276	-0.77177	-0.20523	-0.17685	-0.47456	0.12072
6	0.019615	-0.21027	0.242376	-0.29494	-0.59887	0.008464
7	-0.08239	-0.4787	0.259286	-0.2228	-0.48141	0.028553
8	0.102894	-0.78463	1.150421	-0.02116	-0.38401	0.326528
9	1.037316	0.740287	1.33345	-0.04931	-0.30897	0.209262
10	-0.05488	-0.31367	0.202917	-0.02034	-0.64365	0.61096
11	-0.11387	-0.55359	0.256921	-0.07413	-0.40157	0.291183
12	0.045954	-0.20426	0.294478	-0.21672	-0.50541	0.068
13	-0.36099	-1.16549	0.508187	-0.15521	-0.58381	0.281916
14	0.246437	-0.26774	0.718736	-0.12786	-0.43868	0.201776
15	0.275173	-0.39918	0.872929	-0.12784	-0.43086	0.186337
16	0.580841	0.28107	0.885343	-0.14607	-0.40788	0.139638
17	-0.09065	-0.43321	0.225064	-0.27383	-0.62256	0.083235
18	0.365509	-0.0459	0.788703	-0.083	-0.31575	0.157951
19	0.058013	-0.26892	0.398931	-0.05576	-0.47291	0.359544
20	1.290148	0.415077	2.10217	-0.09884	-0.3334	0.146882
21	0.046185	-0.3043	0.303511	-0.08933	-0.28295	0.107845
22	-0.38452	-0.93595	0.120253	-0.10515	-0.31295	0.09936
23	0.530725	0.132594	0.924517	-0.08851	-0.38557	0.201354

	TIME			SPACE		
Space-Time Comparison	mean	2.5%	97.5%	mean	2.5%	97.5%
24	0.233174	0.051339	0.412292	-0.09064	-0.27643	0.101054
25	0.479656	0.128522	0.800799	-0.20066	-0.50167	0.085208
26	-0.44127	-1.91798	1.068067	0.088394	-0.4335	0.655484
27	-0.002	-0.76356	0.511734	-0.15988	-0.49768	0.160232
28	-0.41667	-1.26582	0.436477	-0.13149	-0.43541	0.181747
29	0.105931	-0.13261	0.342082	-0.09797	-0.31222	0.117376
30	-0.27788	-1.12852	0.588616	-0.07561	-0.41048	0.238967
31	-0.12841	-0.49737	0.190251	-0.14588	-0.46669	0.187104


Region 1
Mean abundance per stop
0 1 2 3 4
0.42 0.53 0.78
Percent forest cover
Region 2
Mean abundance per stop
0 1 2 3 4 5
0.59 0.66 0.81
Percent forest cover
Region 3
Mean abundance per stop
0.0 1.5 3.0
0.39 0.5 0.73
Percent forest cover
Region 4
Mean abundance per stop
0 2 4 6 8
0.43 0.54 0.73
Percent forest cover
Region 5
Mean abundance per stop
0 1 2 3 4
0.37 0.5 0.67
Percent forest cover
Region 6
Mean abundance per stop
0 1 2 3 4
0.57 0.67 0.9
Percent forest cover
Region 7
Mean abundance per stop
0 1 2 3 4
0.45 0.55 0.78
Percent forest cover
Region 8
Mean abundance per stop
0 4 8 12
0.48 0.62 0.78
Percent forest cover


Region 9
Mean abundance per stop
0
4
8
12
0.38
0.59
0.9
Percent forest cover
Region 10
Mean abundance per stop
0
5
15
25
0.47
0.53
0.75
Percent forest cover
Region 11
Mean abundance per stop
0
1
2
3
4
0.4
0.56
0.7
Percent forest cover
Region 12
Mean abundance per stop
0.0
1.5
3.0
0.51
0.66
0.84
Percent forest cover
Region 13
Mean abundance per stop
0.0
1.5
3.0
0.38
0.49
0.6
Percent forest cover
Region 14
Mean abundance per stop
0
1
2
3
4
0.37
0.48
0.64
Percent forest cover
Region 15
Mean abundance per stop
0.0
1.5
3.0
0.44
0.52
0.67
Percent forest cover
Region 16
Mean abundance per stop
0
1
2
3
4
5
0.29
0.46
0.7
Percent forest cover


Region 17
Mean abundance per stop
0
1
2
3
4
0.4
0.53
0.81
Percent forest cover
Region 18
Mean abundance per stop
0.0
1.0
2.0
0.43
0.56
0.74
Percent forest cover
Region 19
Mean abundance per stop
0
5
10
20
0.34
0.51
0.58
Percent forest cover
Region 20
Mean abundance per stop
0
2
4
0.52
0.62
0.76
Percent forest cover
Region 21
Mean abundance per stop
0.0
1.5
3.0
0.43
0.64
0.82
Percent forest cover
Region 22
Mean abundance per stop
0
5
10
20
0.28
0.45
0.77
Percent forest cover
Region 23
Mean abundance per stop
0
1
2
3
4
0.52
0.64
0.77
Percent forest cover
Region 24
Mean abundance per stop
0
5
10
20
0.33
0.48
0.83
Percent forest cover

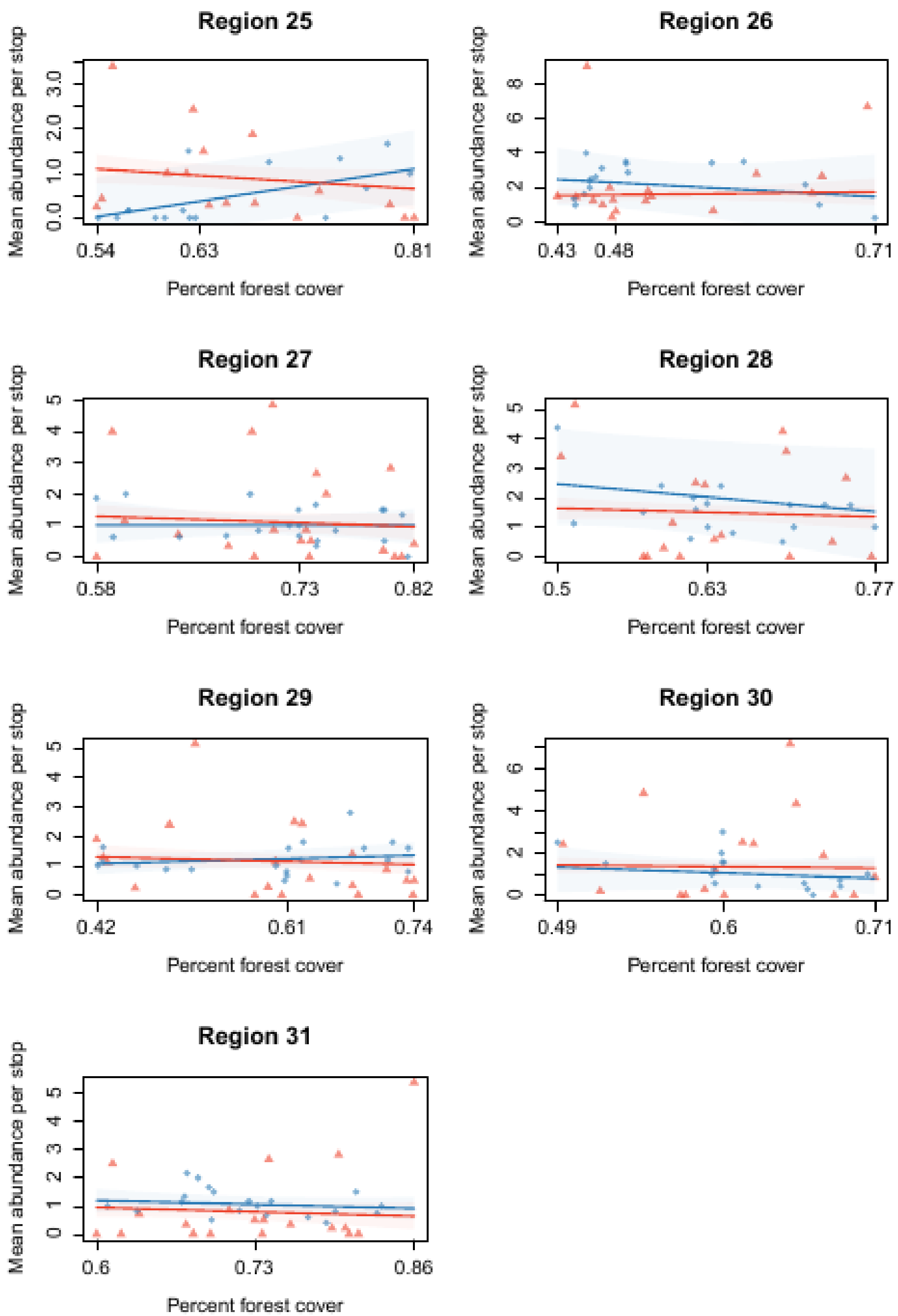


Figure J. Slope estimates (with 95% percentile interval shaded) measuring the effect of forest cover on open-habitat bird mean abundance at a temporal site from 2000 to 2019 (in blue) and in space across a set of neighbouring spatial sites in 2019 (in red) for all 31 space-time comparisons in the U.S. and Canada. Here, each of the spatial slopes were informed by a subset number of eligible spatial sites equal to the number of years informing the corresponding temporal slope.