Horned Grebe weather covariates

Model structure

The model is an elaboration of the iCAR route-level trend model, where the route-level intercepts and slopes are estimates of relative abundances and trends, after accounting for the effects of annual fluctuations caused by route-level annual weather predictors. The route-level predictors are derived from a study of the effects of moisture and drought patterns on Horned Grebe trends in Canada. The annual temperature and precipitation in the region near each BBS route is used to predict annual counts of Horned Grebe on each BBS survey. Annual fluctuations in moisture (precipitation and temperature) have a strong influence on waterbirds in the Prairie Pothole region of Canada. These annual fluctuations complicate assessments of a possible long-term decline in the species' population. This model structure was designed to estimate the long-term rate of population change that is not caused by annual variations in temperature and precipitation.

The model is based on the iCAR models in the main paper, but includes count-level predictors for the effects of precipitation and temperature.

$$C_{r,j,t} = Negative\ Binomial\left(\lambda_{r,j,t}, \phi\right)$$

$$log\left(\lambda_{r,j,t}\right) = \alpha_r + \beta_r * (t - t_m) + \rho_r * precip_{r,t} + \delta_r * temp_{r,t} + \eta \mathrm{I}j,t + \omega j$$

We modeled the observed counts ($C_{r,j,t}$) of Horned Grebes on route-r, in year-t, by observer-j as as realizations of a negative binomial distribution, with mean $\lambda_{r,j,t}$ and inverse dispersion parameter ϕ. The log of the mean ($\lambda_{r,j,t}$) of the negative binomial distribution was modeled as an additive combination of route-level intercepts (α_r), observer-effects (ω_j), and a first-year observer-effect ($\eta I[j,t]$), and route-level slope parameters (β_r) for the continuous effect of year (t) centered on the mid-year of the time-series (t_m).

We estimated the effect of the number of ponds surrounding each route in a given year on BBS counts as a spatially-varying coefficient representing the route-specific effect of local ponds ($\rho_r * ponds_{r,t}$). Where $ponds_{r,t}$ represents the log(1 + number of ponds) surrounding BBS route

r in year t. These values were centered on their mean across years for each route, to ensure we could separately estimate the route-level intercepts and the effects of the annual variations in ponds. The effects of ponds at each route were centered on a mean hyperparameter P, and allowed to vary among routes using the same iCAR spatial structure as for the slopes and intercepts.

$$\rho_r = Normal(P, \sigma_\rho)$$

```
library(bbsBayes)#original version of bbsBayes package
library(tidyverse)
library(sf)
library(cmdstanr)
library(patchwork)

output_dir <- "output"
species <- "Horned Grebe"
source("functions/neighbours_define_voronoi.R") ## function to define neighbourhood relati
source("functions/prepare-data-alt.R") ## small alteration of the bbsBayes function
source("functions/get_basemap_function.R") ## loads one of the bbsBayes strata maps

strat = "bbs_usgs" # standard USGS BBS strata for neighbourhoods and plotting
model = "slope"



species_f <- gsub(gsub(species,pattern = " ",replacement = "_",fixed = T),pattern = "'",re

spp <- "_moisture_"

exp_t <- function(x){
  y <- (exp(x)-1)*100
}

firstYear <- 1975
lastYear <- 2017


out_base <- paste0(species_f,spp,firstYear,"_",lastYear)

sp_data_file <- paste0("Data/",species_f,"_",firstYear,"_",lastYear,"_covariate_stan_data.
```

```r
load(sp_data_file)
mod.file = paste0("models/slope",spp,"route_NB.stan")

slope_model <- cmdstan_model(mod.file, stanc_options = list("Oexperimental"))



stanfit <- slope_model$sample(
  data=stan_data,
  refresh=400,
  iter_sampling=2000,
  iter_warmup=2000,
  parallel_chains = 4)

summ <- stanfit$summary()
print(paste(species, stanfit$time()[["total"]]))

saveRDS(stanfit,
        paste0(output_dir,"/",out_base,"_stanfit.rds"))

saveRDS(summ,
        paste0(output_dir,"/",out_base,"_summ_fit.rds"))

summ %>% arrange(-rhat)
```

Then fit an indentical model without the covariate for comparison of trends.

```r
load(sp_data_file)

mod.file = paste0("models/slope_iCAR_route_NB.stan")

slope_model <- cmdstan_model(mod.file, stanc_options = list("Oexperimental"))

stan_data[["pond"]] <- NULL


stanfit_simple <- slope_model$sample(
  data=stan_data,
  refresh=400,
  iter_sampling=2000,
  iter_warmup=2000,
```

```r
  parallel_chains = 4)

summ_simple <- stanfit_simple$summary()
print(paste(species, stanfit_simple$time()[["total"]]))

saveRDS(stanfit_simple,
        paste0(output_dir,"/",out_base,"_simple_stanfit.rds"))

saveRDS(summ_simple,
        paste0(output_dir,"/",out_base,"_simple_summ_fit.rds"))
```

Fitting the model

To fit the model, we prepared the BBS counts, the neighbourhood structures necessary to estimate the iCAR trend and covariate spatial components, and joined the climate predictor to the data. The full code and data necessary to replicate the data-preparation is available in the online supplement. In brief, we selected all routes on which the species had been observed in the years 1975 - 2017, and for which we had climate data (Prairie-pothole region of Canada).

We fit the model using the probablistic programming language Stan [@standevelopmentteam2022], accessed through the R-package `cmdstanr` [@gabry2022]. We used a warm-up of 2000 iterations, and `cmdstanr` default settings for other arguments, followed by a draw of 2000 samples from which we estimated the posterior distributions. All parameters in all models converged based on Rhat < 1.02 and bulk effective sample sizes > 500.

We also fit a simpler model without the covariate information to the same data, so that we could compare the trend estimates with and without excluding the effects of the annual fluctuations in ponds.

Results

```
pdf
  2
```

During the 43-years from 1975-2017, the species overall population declined at a rate of -1.9 %/year. After removing the effect of annual variations in the number of ponds surrounding each BBS route, the long-term rate of decline was -2.2 %/year. This difference suggests that annual fluctuations in moisture have been responsible for reducing the species' rate of decline. It also suggests that the species' Prairie populations may decline even further, given the predictions for reduced precipitation and higher temperatures in the region with climate change.

The effect of annual fluctuations in the number of ponds was positive across the region, but there was also a spatial gradient in intensity. The effect of number of ponds in a given year was strongest in the western part of the Prairies (Figure S9).

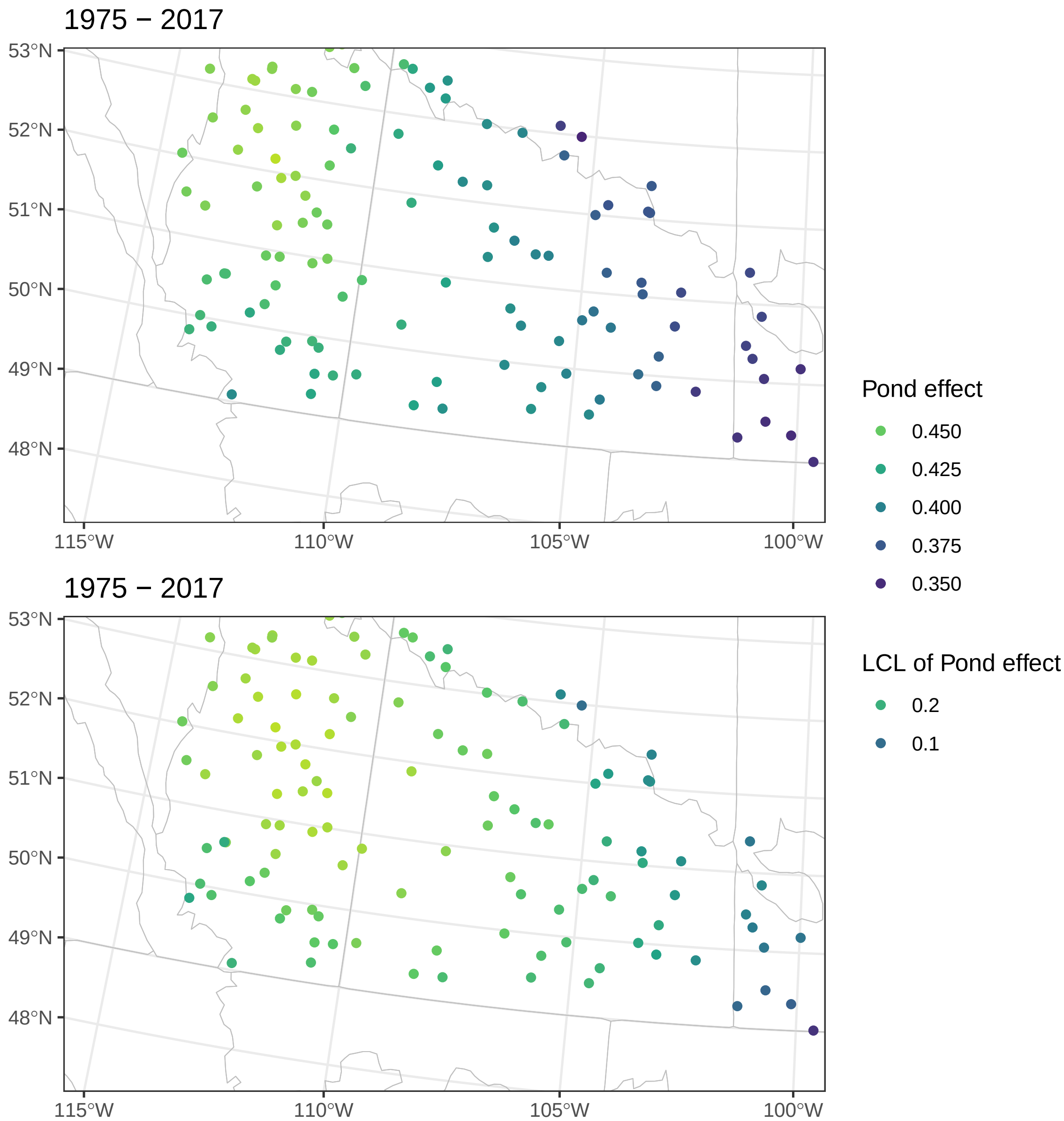

Figure 1: Map of the effect of the number of ponds surrounding each BBS route in a given year on the counts of Horned Grebes, 1975-2010. The colours represent the route-specific coefficient for the effect of the log-transformed count of the number of ponds surrounding each BBS route. The positive values indicate that higher numbers of ponds are correlated with higher counts of Horned Grebes during a given survey. The left plot shows the posterior mean effects at each route and the right panel shows the lower 95% credible limit for the effect. hat habitat suitability accounts for much of the variation in abundance