```
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                                                                                           We will start by importing the climate data from a local rds file.
           In [1]: # Importing tidyverse, raster, and sf packages
                                                                                          library(tidyverse)
                                                                                          library(sf)
                                                                                           library(raster)
                                                                                           # Importing the climate data from an rds file
                                                                                           climate <- read_rds('datasets/climate_raster.rds')</pre>
                                                                                           # Have a look at the variables in the climate data
                                                                                           colnames(climate)
                                                                                           # Converting the dataframe to SpatialPixelDataFrame for plotting
                                                                                           climate_df <- mutate(</pre>
                                                                                                               .data = climate,
                                                                                                               rasters = map(
                                                                                                                              .x = rasters,
                                                                                                                              ~ as_tibble(as(.x, "SpatialPixelsDataFrame")))) %>%
                                                                                                             unnest(cols = c(rasters))
                                                                                             -- Attaching packages ----- tidyverse 1.2.1 --
                                                                                           v ggplot2 3.2.1 v purrr 0.3.3
                                                                                          v tibble 2.1.3 v dplyr 0.8.3
                                                                                           v tidyr 1.0.0
                                                                                                                                                                                                                                                                                      v stringr 1.4.0
                                                                                           v readr 1.1.1 v forcats 0.3.0
                                                                                           -- Conflicts ----- tidyverse_conflicts() --
                                                                                           x dplyr::filter() masks stats::filter()
                                                                                          x dplyr::lag() masks stats::lag()
                                                                                          Linking to GEOS 3.5.1, GDAL 2.2.2, PROJ 4.9.2
                                                                                          Loading required package: sp
                                                                                           Attaching package: 'raster'
                                                                                           The following object is masked from 'package:dplyr':
                                                                                                                                  select
                                                                                           The following object is masked from 'package:tidyr':
                                                                                                                               extract
                                                                                           'decade' 'rasters'
                                                                                           2. Mapping a changing climate
                                                                                           We have loaded the pre-processed climate data and converted it to a SpatialPixelDataFrame. This data frame now contains all the information we
                                                                                           need:
                                                                                                          • the decade of observation,

    spatial coordinates (x, y)

                                                                                                          • six selected climatic variables (minimum.temperature, maximum.temperature, rainfall, wind.speed, snow.lying, air.frost)
                                                                                           The first step in any analysis is visualizing the data. Visualizing the data makes sure the data import worked, and it helps us develop intuition about the
                                                                                           patterns in our dataset. Here we are dealing with spatial datas. We will start with two maps: one map of the climatic conditions in 1970, and one map of the
                                                                                           climatic conditions in 2010. Our climate data has several variables, so let us pick minimum.temperature for now.
           In [2]: library(ggthemes)
                                                                                           # Creating the plot
                                                                                           ggp_temperature <- climate_df %>%
                                                                                                            filter(decade == 1970 | decade == 2010)%>%
                                                                                                                  ggplot(aes(x = x, y = y)) + geom_tile(aes(fill = minimum.temperature)) +
                                                                                                                  theme_map()+
                                                                                                                  coord_equal()+
                                                                                                                facet_grid(~ decade) + scale_fill_distiller(palette = "Spectral") +
                                                                                                                theme(legend.title = element_blank(), legend.position = "bottom") +
                                                                                                               labs(title = "Minimum temperature (Celsius)", caption = 'Source: MetOffice UK')
                                                                                             ggp_temperature
                                                                                                        Minimum temperature (Celsius)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      2010
                                                                                                                     0.0 2.5 5.0 7.5
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               Source: MetOffice UK
                                                                                           3. Fieldwork in the digital age – download the data
                                                                                           Now we need to obtain species occurrence records. This used to be the main challenge in biogeography. Natural historians, such as Charles Darwin and
                                                                                           Alexander von Humboldt, traveled around the globe for years on rustic sail ships collecting animal and plant specimens to understand the natural world. Today,
                                                                                           we stand on the shoulders of giants. Getting data is fast and easy thanks to two organizations:
                                                                                                          • The Global Biodiversity Information Facility (GBIF), an international network and research infrastructure aimed at providing anyone, anywhere, open
                                                                                                                          access to data about life on Earth. We will use their data in this project.
                                                                                                          • rOpenSci, a non-profit initiative that develops open source tools for academic data sets. Their package rgbif will help us access the species data.
           In [3]: library(rgbif)
                                                                                           source("datasets/occ_search.R")
                                                                                           # Calling the API to get the occurrence records of Scottish crossbill
                                                                                           gbif_response <- occ_search(</pre>
                                                                                                             scientificName = "Loxia scotica", country = "GB",
                                                                                                             hasCoordinate = TRUE, hasGeospatialIssue = FALSE, limit = 2000)
                                                                                             # Inspecting the class and names of gbif_response
                                                                                           class(gbif_response)
                                                                                           names(gbif_response)
                                                                                           head(data, n = 6)
                                                                                           'meta' 'hierarchy' 'data' 'media' 'facets'
                                                                                           1 function (..., list = character(), package = NULL, lib.loc = NULL,
                                                                                                                                                    verbose = getOption("verbose"), envir = .GlobalEnv)
                                                                                          3 {
                                                                                                                                                    fileExt <- function(x) {</pre>
                                                                                                                                                                                          db \leftarrow grepl("\\.[^.]+\\.(gz|bz2|xz)$", x)
                                                                                                                                                                                           ans <- sub(".*\\\.", "", x)
                                                                                           4. Sorting out the bad eggs – data cleaning
                                                                                           In particular, data collected at this large scale can have issues. Luckily, GBIF provides some useful metadata on each record.
                                                                                           Here are some criteria we can use:
                                                                                                       1. "issues" - We will only use records where no doubts about the observation were listed.
                                                                                                          2. "license" - We will only use records under a creative commons license.
                                                                                                          3. "date" - We will only use records between 1965 and 2015 because that matches our climate dataset.
           In [4]: library(lubridate)
                                                                                           birds_dated <- mutate(</pre>
                                                                                                            .data = gbif_response$data,
                                                                                           # Creating a new column which specifies the decade of observation
                                                                                                          decade = ymd_hms(eventDate) %>% round_date("10y") %>% year())
                                                                                           birds_cleaned <- birds_dated %>%
                                                                                                               filter(
                                                                                                                              issues == "" &
                                                                                                                               str_detect(license, "http://creativecommons.org/") &
                                                                                                                               decade >= 1970, decade <= 2010
                                                                                                               transmute(decade = decade, x = decimalLongitude, y = decimalLatitude) %>%
                                                                                                               arrange(decade)
                                                                                           Attaching package: 'lubridate'
                                                                                           The following object is masked from 'package:base':
                                                                                                                               date
                                                                                           5. Nesting the data
                                                                                           We have cleaned the data, but there is a problem. We want to know the climatic conditions at the location of the bird observation at the time of the
                                                                                           observation. This is tricky because we have climate data from multiple decades. How do we match each bird observation to the correct climate raster cell?
                                                                                           We can nest() data in a list column. The result is a data frame where the grouping columns do not change, and a list column of aggregated data from each
                                                                                           group is added. List columns can hold many different kinds of variables such as vectors, data frames, and even objects. For example, the climate data that we
                                                                                           imported earlier was already nested by decade and had a list column (rasters) that contained a rasterStack object for each decade.
           In [5]: # "Nesting" the bird data
                                                                                           birds_nested <- birds_cleaned %>%
                                                                                                                               group_by(decade) %>%
                                                                                                                               nest(.key = "presences")
                                                                                             head(birds_nested)
                                                                                             # Calculating the total number of records per decade
                                                                                           birds_counted <- birds_nested %>%
                                                                                                            mutate(n = map_dbl(presences, nrow))
                                                                                           head(birds_counted)
                                                                                           Warning message:
                                                                                               "`.key` is deprecated"
                                                                                                   decade
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    presences
                                                                                                                  1970
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   -3.7742, -3.7996, -3.7424, -3.7742, -3.7536, 57.1484, 57.1748, 57.1368, 57.1484, 57.2490
                                                                                                                  1980
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        -3.805402, -3.604524, -4.323717, -3.712700, 57.164144, 57.327101, 56.670186, 57.163600
                                                                                                                                                                                                                                   -3.957270, -3.626685, -3.702624, -3.957270, -3.957270, -3.604524, -3.680281, -3.175040, -3.604524, \\ 54.930540, 57.227079, 57.241025, 54.930540, 54.930540, \\ 54.930540, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, \\ 54.930540, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.604524, -3.
                                                                                                                  1990
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                                                                                           6. Making things spatial - projecting our observations
                                                                                           Both our datasets are nested by decade now. We have one more step before we extract the climatic conditions at bird locations. Locations in
                                                                                               birds_counted are latitude and longitude coordinates. R doesn't know that these are spatial information. We need to convert and project our data.
                                                                                           Projections are necessary because maps are 2-dimensional, but the earth is 3-dimensional. There is no entirely accurate way to represent the surface of a 3D
                                                                                           sphere in 2D. Projections are sets of conventions to help us with this issue. GBIF hosts data from around the world and uses a global projection (WGS84). The
                                                                                           Met Office is a UK organization and provides data in the British National Grid projection (BNG).
                                                                                                 To project spatial data, use Coordinate Reference System (CRS) strings
           In [6]: # Define geographical projections
                                                                                           proj_latlon <- st_crs("+proj=longlat +datum=WGS84 +ellps=WGS84 +towgs84=0,0,0")</pre>
                                                                                           proj_ukgrid <- st_crs("+init=epsg:27700")</pre>
                                                                                             # Converting records to spatial points and projecting them
                                                                                           birds_presences <- mutate(birds_counted,</pre>
                                                                                                            presences = map(presences, ~ .x %>%
                                                                                                                              # Specifying the current projection
                                                                                                                               st_as_sf(coords = c("x", "y"), crs = proj_latlon) %>%
                                                                                                                               # Transforming to new projection
                                                                                                                               st_transform(crs = proj_ukgrid)))
                                                                                           7. Extracting key information
                                                                                           Now we are ready to combine the two datasets and extract the climatic conditions at each location for the given decade. This is where the nested structure
                                                                                           comes in handy. We join the data frames by their grouping column and can rest assured that the data in the list columns are matched up correctly. This allows
                                                                                           us to operate on the list column variables element-wise using the map() family functions.
           In [8]: | # Combining the bird data and the climate data in one data frame
                                                                                           birds_climate <- full_join(birds_presences, climate, by = "decade")</pre>
                                                                                           presence_data <- map2_df(</pre>
                                                                                                          .x = birds_climate[["rasters"]],
                                                                                                            .y = birds_climate[["presences"]],
                                                                                             # extracting the raster values at presence locations
                                                                                                            ~ raster::extract(x = .x, y = .y) \%
                                                                                                                               as_tibble() %>%
                                                                                                                                  mutate(observation = "presence"))
                                                                                           8. Pseudo-absences
                                                                                           To run a machine learning model, the classification algorithm needs two classes: presences and absences. Our presences are the observations from GBIF.
                                                                                           Absences are a lot harder to get.
                                                                                           The difficulty is because of information asymmetry between the presences and absences. With a bird observation we are sure it occurred at that location, but
                                                                                           to be certain the bird does not occur somewhere, we would have to continuously monitor the site.
                                                                                           One way to deal with this problem is to generate "pseudo-absences". Pseudo-absences are a random sample from the entire study area. We assume that the
                                                                                           species does not occur at the random locations and our hope is that the average actual probability of occurrence for the bird in these random locations is low
                                                                                           enough to give our algorithm something to learn
           In [9]: # Defining helper function in order to create pseudo-absence data
                                                                                           create_pseudo_absences <- function(rasters, n, ...) {</pre>
                                                                                                                               set.seed(12345)
                                                                                                                                  sampleRandom(rasters, size = n * 5, sp = TRUE) %>%
                                                                                                                               raster::extract(rasters, .) %>% as_tibble() %>%
                                                                                                                               mutate(observation = "pseudo_absence")
                                                                                           # Creating pseudo-absence proportional to the total number of records per decade
                                                                                           pseudo_absence_data <- pmap_df(.1 = birds_climate, .f = create_pseudo_absences)</pre>
                                                                                           # Combining the two datasets
                                                                                           model_data <- full_join(presence_data, pseudo_absence_data) %>%
                                                                                                          mutate(observation = factor(observation)) %>% na.omit()
                                                                                           Joining, by = c("minimum.temperature", "maximum.temperature", "rainfall", "wind.speed", "snow.lying", "air.frost", "o
                                                                                           bservation")
                                                                                           9. Making models - with caret
                                                                                           We are ready to train our model. We will use glmnet, which fits a generalized logistic regression (glm) with elastic net regularization (net). Our algorithm has
                                                                                           several "hyperparameters". These are variables used by the machine learning algorithm to learn from the data. They influence the performance of the model
                                                                                           and often interact with one another, so it is difficult to know the right settings apriori.
                                                                                           To figure out a good set of hyperparameters, we need to try several possible scenarios to see which ones work best. caret makes this easy. All we need to
                                                                                           do is define a "tuning grid" with sets of possible values for each training parameter. Then use cross-validation to evaluate how well the different combinations
                                                                                           of hyperparameters did building the predictive model.
In [10]: # Importing caret and setting a reproducible seed
                                                                                           library(caret)
                                                                                           set.seed(12345)
                                                                                           # Create a tuning grid with sets of hyperparameters to try
                                                                                           tuneGrid <- expand.grid(alpha = c(0, 0.5, 1), lambda = c(.003, .01, .03, .06))
                                                                                           # Create settings for model training
                                                                                           trControl <- trainControl(method = 'repeatedcv', number = 5, repeats = 1,</pre>
                                                                                                            classProbs = TRUE, verboseIter = FALSE, summaryFunction = twoClassSummary)
                                                                                             # Fitting a statistical model to the data and plot
                                                                                             model_fit <- train(</pre>
                                                                                                            observation ~ ., data = model_data,
                                                                                                             method = "glmnet", family = "binomial", metric = "ROC",
                                                                                                             tuneGrid = tuneGrid, trControl = trControl)
                                                                                             plot(model_fit)
                                                                                           Loading required package: lattice
                                                                                           Attaching package: 'caret'
                                                                                           The following object is masked from 'package:purrr':
                                                                                                                               lift
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           Mixing Percentage
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          0.5 • ----
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            1 0 —
                                                                                                                                              0.950
                                                                                                    ROC (Repeated Cross-Validation)
                                                                                                                                              0.945
                                                                                                                                             0.940
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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          Regularization Parameter
                                                                                           10. Prediction probabilities
                                                                                           We have now built our first species distribution model. Next, we will use it to predict the probability of occurrence for Scottish crossbill across the UK. We will
                                                                                           make a prediction for each decade and each cell of the grid. Since we fit a logistic regression model, we can choose to predict the probability. In our case, this
                                                                                           becomes the "probability of occurrence" for our species.
In [11]: # Use the model to make a prediction
```

1. Tracking a changing climate

may be interested in studying.

The climate is changing around the world. The impacts of climate change are felt in many different areas, but they are particularly noticeable in their effects on

distribution model using machine learning. This model will be able to predict where our bird species of interest is likely to occur in the future - information that

In this project, we will model the Scottish crossbill (*Loxia scotica*). The Scottish crossbills is a small bird that inhabits the cool Scottish forests and feeds on pine seeds. Only ~ 20,000 individuals of this species are alive today. The code and the data sources in this project can be reapplied to any other species we

Our analysis will use data from the UK Met Office together with records from the Global Biodiversity Information Facility to build our very own species

birds. Many bird species are moving north, if they can, to stay in climatic conditions that are suitable for them.

is invaluable to conservation organization working on the ground to preserve these species and save them from extinction.

geom_tile(aes(fill = prediction)) +

climate_df[["prediction"]] <- predict(</pre>

type = "prob")[["presence"]]

decade minimum.temperature maximum.temperature

5.180083

4.422417

5.199667

4.771250

5.486250

4.464667

11. Visualizing the predictions

object = model_fit,
newdata = climate_df,

head(climate_df)

1970

1970

1970

1970

1970

1970

In [12]: library(viridis)

Creating the plot

theme_map()+
coord_equal()+

Habitat Suitability

ggp_changemap <- climate_df %>%
 ggplot(aes(x = x, y = y)) +

viridisLite

rainfall wind.speed snow.lying

14.66736

18.30500

12.15764

11.51333

11.77028

15.10250

It would be great to visualize the predictions so we can see the patterns and how they change over time. A picture says more than a thousand words. We will

We have our predictions, but they are not in a digestible format. It is tough to figure out what is going on from that large table of numbers.

9.764917 101.50867

9.324833 114.34383

119.00492

74.00758

71.86208

92.30558

8.400500

10.947667

10.619250

10.478667

create another map that shows our predictions of a changing climate in the UK, from 1965 to 2015.

scale_fill_viridis(option = "A") + theme(legend.position = "bottom") +

air.frost

0.888750 2.541167 227500 972500 0.03820425

1.768333 3.757833 232500 972500 0.04426503

1.241000 3.136417 307500 972500 0.10089482

1.569750 4.126000 322500 972500 0.21359648

1.107833 2.875833 222500 967500 0.06564189

1.477417 4.422417 227500 967500 0.05684158

y prediction

Habitat Suitability [0 low - high 1]

Outside Source:

GBIF data and MetOffice UK climate data