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SimpleSDMLayers.jl and GBIF.jl: A Framework for Species Distribution Modelling in Julia

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Software

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Summary

Predicting where species should be found in space is a common question in Ecology and Biogeography. Species distribution models (SDMs), for instance, aim to predict where environmental conditions are suitable for a given species on continuous geographic scales. Such analyses require the use of geo-referenced data on species distribution coupled with climate or land cover informations, hence a tight integration between environmental data, species occurrence data, and spatial coordinates. Thus, it requires an efficient way to access species occurrence and environmental data within the same software, as well as a solid framework on which to build analyses based on occurrence data. Here we present `SimpleSDMLayers.jl` and `GBIF.jl`, two packages in the *Julia* language implementing a framework and type-system on which to build SDM analyses, as well as providing access to popular data sources for species occurrence and environmental conditions.

Statement of need

Species distribution modelling (SDM) is an increasingly growing field in Ecology and Biogeography, with many applications in biodiversity assessment, management, and conservation (Araújo et al., 2019). Most SDM models aim at predicting a species distribution in space based on environmental data and information on where the species was previously seen. Hence, SDM studies require a tight and efficient integration between geo-referenced environmental and species occurrence data. However, such data are complex to handle and often require different software: climate and land use data are stored as layers in raster files, then visualized and manipulated in specialized GIS (geographic information systems) software, while occurrence data are stored in tables and spreadsheets sent through data analysis and statistics-oriented tools or programming languages. There is therefore a need for efficient tools to manipulate bioclimatic data in all programming languages, specifically oriented towards species distribution modelling.

In recent years, *R* (R Core Team, 2020) has become the most widely used programming language in Ecology, especially in spatial ecology studies (Lai, Lortie, Muenchen, Yang, & Ma, 2019). Hence, many efficient packages and tools for species distribution modelling have been developed in *R*. For instance, the package `raster` (Hijmans, 2020) can be used to manipulate raster format data (for example climatic or land use data), `dismo` (Hijmans, Phillips, Leathwick, & Elith, 2017) implements many SDM models and provides access to common climatic data sources, and `rgbif` (Chamberlain et al., 2020) provides access to the GBIF database, a common source of species occurrence data in SDM studies. Yet, few SDM resources currently exist for the *Julia* language (Bezanson, Edelman, Karpinski, & Shah,

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2017), although its speed and efficiency at numerical computing could be very useful in SDMs. There are currently packages such as `GDAL.jl` and `ArchGDAL.jl` to manipulate raster data; however these are lower level implementations than what is typically used by most ecologists and they support for common layer manipulation features in SDM studies.

`SimpleSDMLayers.jl` is a package to facilitate manipulation of geo-referenced raster data in *Julia*, aimed specifically at species distribution modelling. It is a higher level implementation, building on `ArchGDAL.jl`, that is easier to use and provides support for common SDM operations. The package implements simple type structures to manipulate the data, and is meant to be a flexible framework on which to build complex SDM analyses. `SimpleSDMLayers.jl` also offers an built-in access to some of the most common data sources in SDM studies, such as the WorldClim 2.1 climatic data, which is the most common source of climate data in SDM studies (Booth, Nix, Busby, & Hutchinson, 2014). The package is also tightly integrated with `GBIF.jl`, which allows easy access to the GBIF database, a common data source for the species occurrences. Both `SimpleSDMLayers.jl` and `GBIF.jl` are part of the *EcoJulia* organization, whose aim is to integrate a variety of packages for ecological analyses in *Julia*.

Basic structure

The core structure implemented in the package is the `SimpleSDMLayer` type, with two variants, `SimpleSDMPredictor` and `SimpleSDMResponse`, depending if the layer is meant to be mutable or not.

A `SimpleSDMLayer` element is made of a `grid` field, which contains the raster data as a simple `Array` (matrix) of any type, easily manipulable. It also contains the fields `left`, `right`, `bottom` and `top`, representing the bounding coordinates of the layer.

To illustrate this structure, the following code loads a layer of WorldClim 2.1 climate data, which also shows how easily this can be done in a single call. By default, this will return a layer with the values for the whole world if no bounding coordinates are specified.

```julia
using SimpleSDMLayers

# Get world temperature data
temperature = worldclim(1)
```

```
SimpleSDMLayers.SimpleSDMPredictor{Float32}(Union{Nothing, Float32}[-31.017
105f0 -31.62153f0 … -32.81253f0 -31.620333f0; -30.391916f0 -31.63478f0 … -3
2.81005f0 -30.995281f0; … ; nothing nothing … nothing nothing; nothing noth
ing … nothing nothing], -180.0, 180.0, -90.0, 90.0)
```

The raster values can be displayed by calling the `grid` field.

```julia
# Display data grid
temperature.grid
```

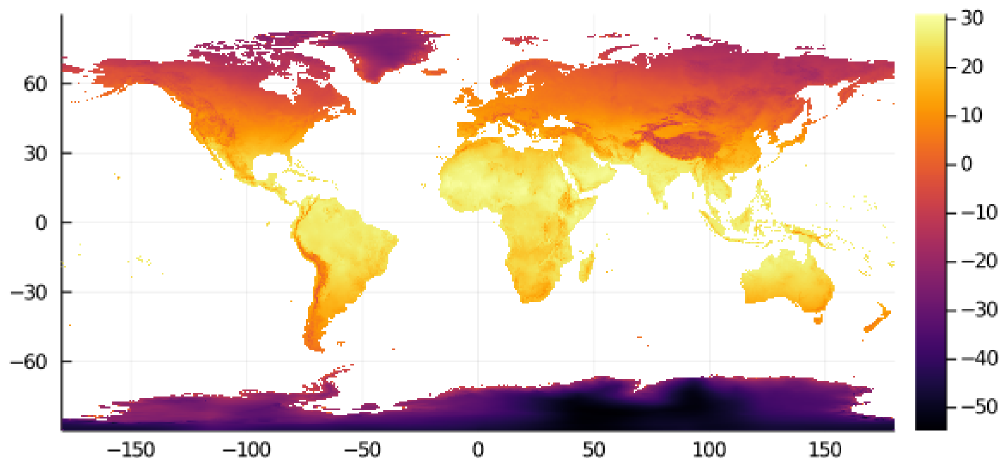
```
1080×2160 Array{Union{Nothing, Float32},2}:
 -31.0171    -31.6215    -31.6227    …  -32.8129    -32.8125    -31.6203
 -30.3919    -31.6348    -31.6341       -32.8092    -32.8101    -30.9953
 -33.4822    -34.1494    -34.1493       -35.4658    -35.4633    -34.1374
 -33.6104    -34.2875    -34.2865       -35.596     -35.5931    -34.2528
 -33.7199    -34.4041    -34.4014       -35.6932    -35.691     -34.3311
```

```
-33.8224    -34.5184    -34.5162    …  -35.8037    -35.7996    -34.4165
-31.6613    -32.3194    -32.3184       -33.5133    -33.5101    -32.2032
-31.7635    -32.4307    -33.7036       -34.9522    -33.6282    -32.3038
-33.7063    -36.0738    -39.2075       -40.6438    -37.3938    -34.3026
-33.9768    -34.7016    -35.8662       -37.2408    -36.0364    -34.5988

   nothing     nothing     nothing        nothing     nothing     nothing
   nothing     nothing     nothing        nothing     nothing     nothing
   nothing     nothing     nothing        nothing     nothing     nothing
   nothing     nothing     nothing        nothing     nothing     nothing
   nothing     nothing     nothing  …     nothing     nothing     nothing
   nothing     nothing     nothing        nothing     nothing     nothing
   nothing     nothing     nothing        nothing     nothing     nothing
   nothing     nothing     nothing        nothing     nothing     nothing
   nothing     nothing     nothing        nothing     nothing     nothing
```

`SimpleSDMLayers.jl` then makes it very simple to plot and visualize the layer as a map using `Plots.jl`.

```
using Plots
plot(temperature)
```



Feature overview

`SimpleSDMLayers.jl` implements the following features:

- **Overloads for common functions**: The `SimpleSDMLayer` types are implemented along with overloads for many common functions and operations, such as subsetting, changing values, copying, and iterating. Therefore, the layers and the raster values stored in the `grid` field can be manipulated as easily as any `Array`, without losing their spatial aspect.

- **Statistical operations on layer values**: Common operations can be performed directly on the layer values without worrying about the underlying structure (for example, sum, minimum, maximum, mean, median).
- **Statistical operations on multiple layers**: Operations can also be performed between layers to produce a new layer, just as `Arrays`, as long as they share the same coordinates. For instance, two layers can be added or subtracted, and calling `mean()` will produce a new layer with the mean value per pixel.
- **Spatial operations**: `SimpleSDMLayers.jl` implements spatial operations such as clipping a layer to given coordinates, coarsening the resolution by grouping values, and performing sliding window operations given a certain radius.
- **Datasets supported**: The package provides access to climate data at different resolutions from WorldClim 2.1 and CHELSA, as well as land cover data from EarthEnv. Custom raster data can be loaded as well.
- **Plotting recipes**: Default recipes are implemented for the `SimpleSDMLayer` types, allowing to directely map them, view the grid values data as histograms and density plots, or compare layers as 2-dimensional histograms.
- **Integration with GBIF.jl (and DataFrames.jl)**: `SimpleSDMLayer.jl` is well integrated with `GBIF.jl`, allowing to clip layers based on the occurrence data. Both also offer an integration with `DataFrames.jl` to easily convert environmental and occurrence data to a table format.

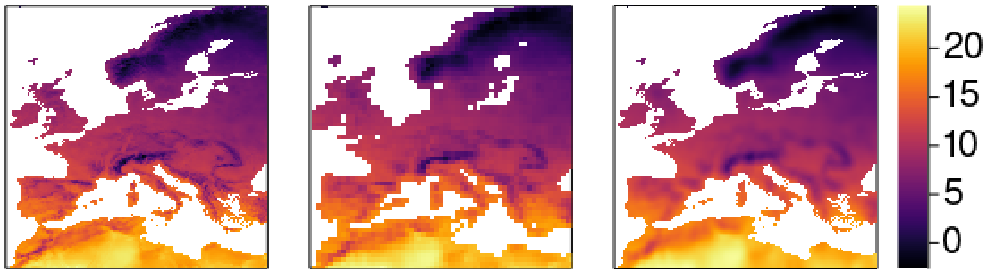
Examples

Spatial operations

To illustrate a few of the spatial operations supported by `SimpleSDMLayers.jl`, the following code reuses the previous `temperature` layer, and shows how it is possible to : 1) clipping the layer a region of interest (Europe for instance); 2) coarsening the resolution by averaging groups of cells for large scale analyses; and 3) performing sliding window operations to aggregate values for each site based on a certain radius. Each of these operations can be performed in a single command and returns new layers, which can then be plotted.

```
using Statistics
# Clip to Europe
temperature_europe = temperature[left = -11.2, right = 30.6, bottom = 29.1, top =
# Coarsen resolution
temperature_coarse = coarsen(temperature_europe, Statistics.mean, (4, 4))
# Sliding window averaging
temperature_slided = slidingwindow(temperature_europe, Statistics.mean, 100.0)
```

```
SimpleSDMLayers.SimpleSDMPredictor{Any}(Any[nothing nothing … 20.822838f0 2
0.985363f0; nothing nothing … 20.735191f0 20.890547f0; … ; nothing nothing
… nothing nothing; nothing nothing … nothing nothing], -11.333333333333334,
 30.666666666666664, 29.0, 71.0)
```



GBIF integration

As an example of the integration between `SimpleSDMLayers.jl` and `GBIF.jl`, lets focus on the case of a single species, the Belted Kingfisher (*Megaceryle alcyon*). `GBIF.jl` first allows us to retrieve the latest occurrences from the GBIF database.

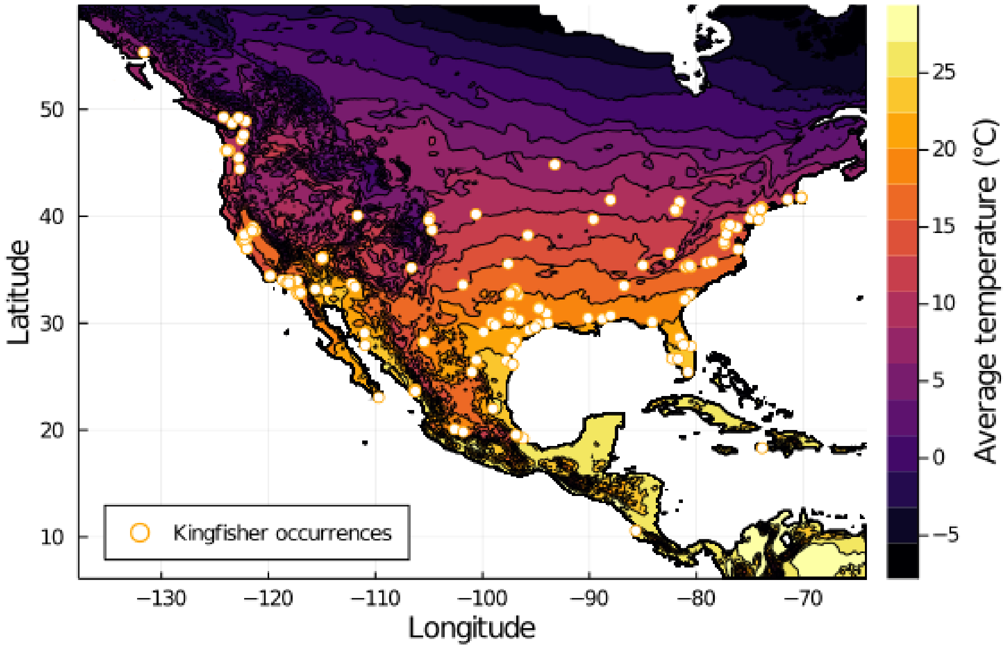
```
using GBIF
kingfisher = GBIF.taxon("Megaceryle alcyon", strict=true)
kf_occurrences = occurrences(kingfisher)
# Get at least 200 occurrences
while length(kf_occurrences) < 200
    occurrences!(kf_occurrences)
    @info "$(length(kf_occurrences)) occurrences"
end
kf_occurrences
```

```
GBIF records: downloaded 200 out of 100000
```

Then, `SimpleSDMLayers.jl` integrates this data and can combine it with the environmental layers, allowing to clip the layers to the extent of the occurrences. Finally, it is very straightforward to create a map of the occurrences by overlaying them on top of the environmental data.

```
# Clip layer to occurrences
temperature_clip = clip(temperature, kf_occurrences)

# Plot occurrences
contour(temperature_clip, fill=true, colorbar_title = "Average temperature (°C)",
                  xguide = "Longitude", yguide = "Latitude")
scatter!(longitudes(kf_occurrences), latitudes(kf_occurrences),
         label = "Kingfisher occurrences", legend = :bottomleft,
         c = :white, msc = :orange)
```



Acknowledgements

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