

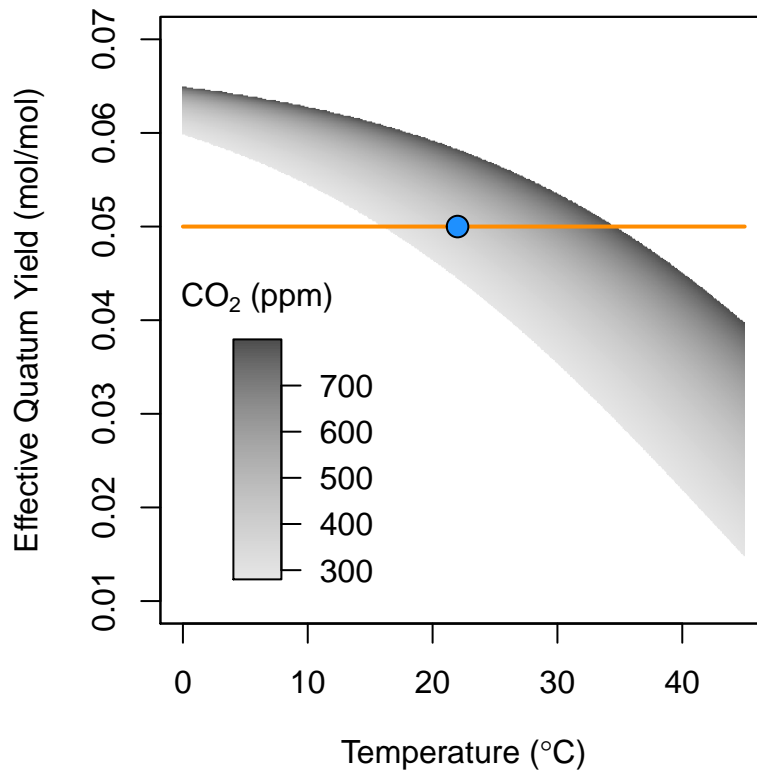
# Modeling the terrestrial distribution of plant carbon stable isotopes in R

*Daniel M Griffith, Rebecca L Powell, Sydney Firmin, Jen Cotton, & Christopher J Still*

*June 2018*

## Introduction & Objectives

Our goal is to predict plant tissue  $\delta^{13}\text{C}$  variation across a landscape. The primary driver of variation in plant  $\delta^{13}\text{C}$  is the greater isotopic fractionation in  $\text{C}_3$  plants compared to  $\text{C}_4$  plants. The crossover temperature model is a physiologically based model that explains the turnover from  $\text{C}_3$  to  $\text{C}_4$  plants along gradients of temperature (Ehleringer et al., 1997; Collatz et al., 1998; Still et al., 2003). Note that  $\delta^{13}\text{C}$  also varies with photosynthetic subtype in  $\text{C}_4$  plants and with rainfall in woody  $\text{C}_3$  plants (Cerling & Harris, 1999; Diefendorf et al., 2010; Kohn, 2010). Below, the shaded regions shows the effect of  $\text{CO}_2$  and temperature on the light use efficiency of  $\text{C}_3$  plants, and illustrates the temperature at which  $\text{C}_3$  efficiency drops below that of the average  $\text{C}_4$  plant.



We will combine the crossover temperature model with data on land cover and climate to produce map of  $\text{C}_3$  and  $\text{C}_4$  plants in North America. Then, we will apply isotopic endmember values to produce a spatially continuous representation of the  $\delta^{13}\text{C}$  distribution across the continent. These layers are useful for

understanding grass biogeography and for studies seeking to identify the movement of animals (e.g., Hobson, 1999; Powell et al., 2012)

The code for this workflow is a work in progress, and we are developing an R package that will allow all of the pieces to be applied in customized pipelines. This package is called “grassmapr” and is installed below.

This workflow also requires learning some basic functionality in the raster R package.

## Installation

Installation requires GitHub.

```
install.packages("devtools", repos = "http://cran.us.r-project.org")
library(devtools)
install_github(repo = "rebeccapowell/grassmapr")
library(grassmapr)
```

## Load North America example data

Now we need to load and organize the spatial datasets that we will use.

```
tmp <- tmpMeanNA      # Mean Monthly Temperature (deg. C)
pre <- preMeanNA      # Mean Monthly Precipitation (mm)
woody <- woodyNA      # Woody Cover (%)
C3crop <- cropC3NA     # C3 Crop Cover (%)
C4crop <- cropC4NA     # C4 Crop Cover (%)
```

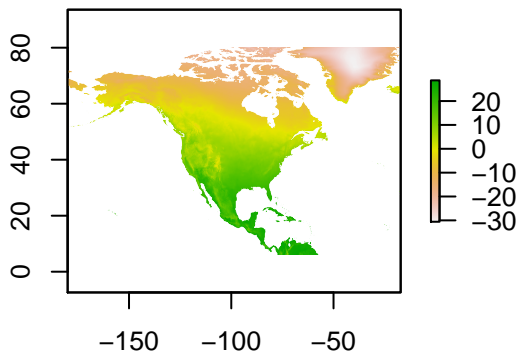
The rainfall and temperature data are monthly climatologies, and so we might want to visualize them here as annual means.

```
annual_tmp <- calc(tmp, fun = mean)
annual_pre <- calc(pre, fun = sum)
```

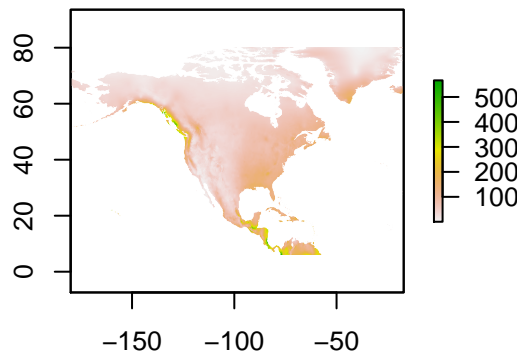
And, now we should plot the data. Based on the crossover temperature model, where would you expect to find C4 grasses?

```
par(mfrow = c(2,2))
plot(annual_tmp,
     main = expression(paste("Mean Annual Temperature (", ~degree, "C)", sep = "")))
plot(annual_pre,
     main = expression(paste("Total Annual Precipitation (mm)", sep = "")))
plot(woody,
     main = expression(paste("Woody % Cover", sep = "")))
plot(C4crop,
     main = expression("C"[4]~"Crops (%))")
```

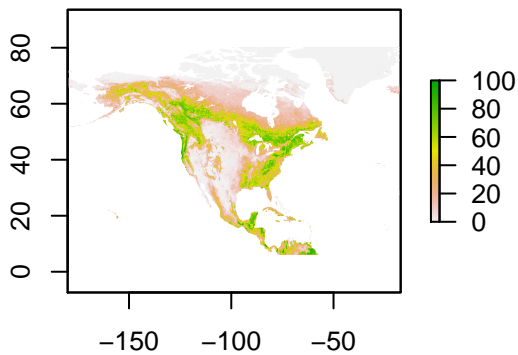
Mean Annual Temperature ( °C)



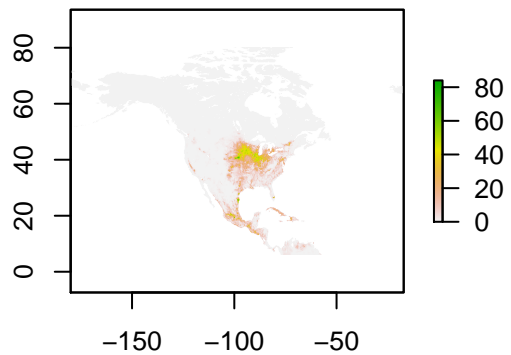
Total Annual Precipitation (mm)



Woody % Cover



C<sub>4</sub> Crops (%)



We should ensure that all data have the same spatial extent and resolution.

```
compareRaster(tmp,
               pre,
               woody,
               C4crop,
               C3crop)
```

If these layers did not have the same extent and resolution, we could use the function `resample()` in order to make these layers compatible with each other.

## A Workflow to produce a C<sub>3</sub> and C<sub>4</sub> distribution map for North America

First, set a temperature threshold based on the crossover temperature model. In addition, set a minimum monthly precipitation threshold - to identify locations that have sufficient moisture to support C<sub>4</sub> grasses (for example, to exclude deserts and Mediterranean climates).

```

# Set a temperature threshold for the COT model
temp.threshold <- 22
# Set a precipitation threshold
precip.threshold <- 25
# Set a growing season temperature threshold
gs.threshold <- 5

```

Create masks of climate layers that represent growing season months and months that favor C<sub>4</sub> plants.

```

# Growing season precipitation mask (>= 25 mm)
precip_mask <- maskClimateVals(pre, precip.threshold)
# Growing season temperature mask (>= 5 deg. C)
GS_temp_mask <- maskClimateVals(tmp, gs.threshold)
# C4 temperature mask (>= 22 deg. C)
C4_temp_mask <- maskClimateVals(tmp, temp.threshold)

# Generate Growing Season (GS) climate masks
GS_mask <- combineMasks(GS_temp_mask, precip_mask)
# Generate C4 climate masks
C4_mask <- combineMasks(C4_temp_mask, precip_mask)

```

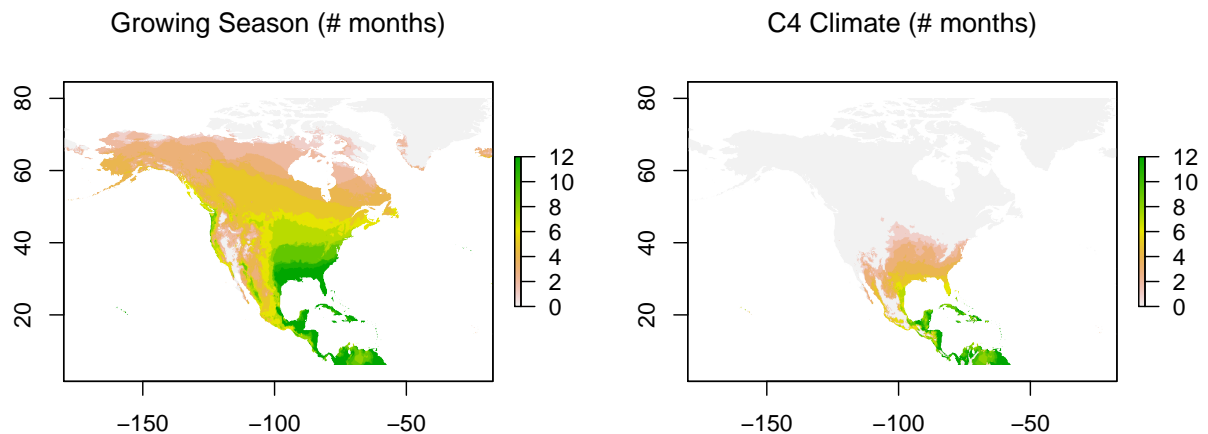
We can count the monthly masks to get an annual representation of the number of growing season months and C<sub>4</sub> months.

```

# Count number of months that satisfy each climate criteria
GS_month_total <- countMonths(GS_mask)
C4_month_total <- countMonths(C4_mask)

par(mfrow = c(1,2))
plot(GS_month_total,
     main = expression(paste("Growing Season (# months)", sep = "")),
     zlim = c(0, 12))
plot(C4_month_total,
     main = expression(paste("C4 Climate (# months)", sep = "")),
     zlim = c(0, 12))

```

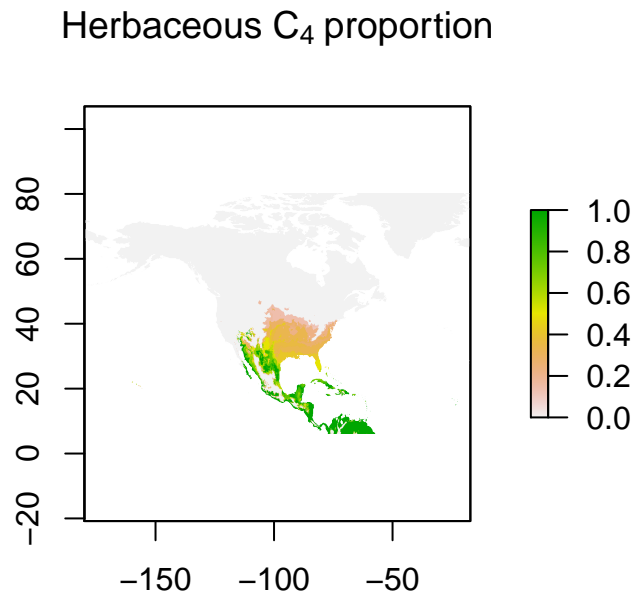


With these two monthly climate masks [and, optionally, monthly NDVI layers], we can calculate the proportion of the herbaceous layer that is C<sub>4</sub>. Note this is different than predicting *actual* vegetation cover.

```
# Calculate C4 ratio based on C4 climate only
C4_ratio <- calcC4Ratio(C4_mask, GS_mask)

# [Optionally:] Calculate C4 ratio based on C4 climate AND vegetation productivity
# C4_ratio_vi <- calcC4Ratio(C4_mask, GS_mask, veg.index = ndvi)

par(mfrow = c(1,1))
plot(C4_ratio, main = "Herbaceous C" [4] ~"proportion")
```



Combine the herbaceous C<sub>4</sub> proportion with other vegetation layers such as woody cover and crop cover. [Note: Other vegetation layers must be provided by the user.]

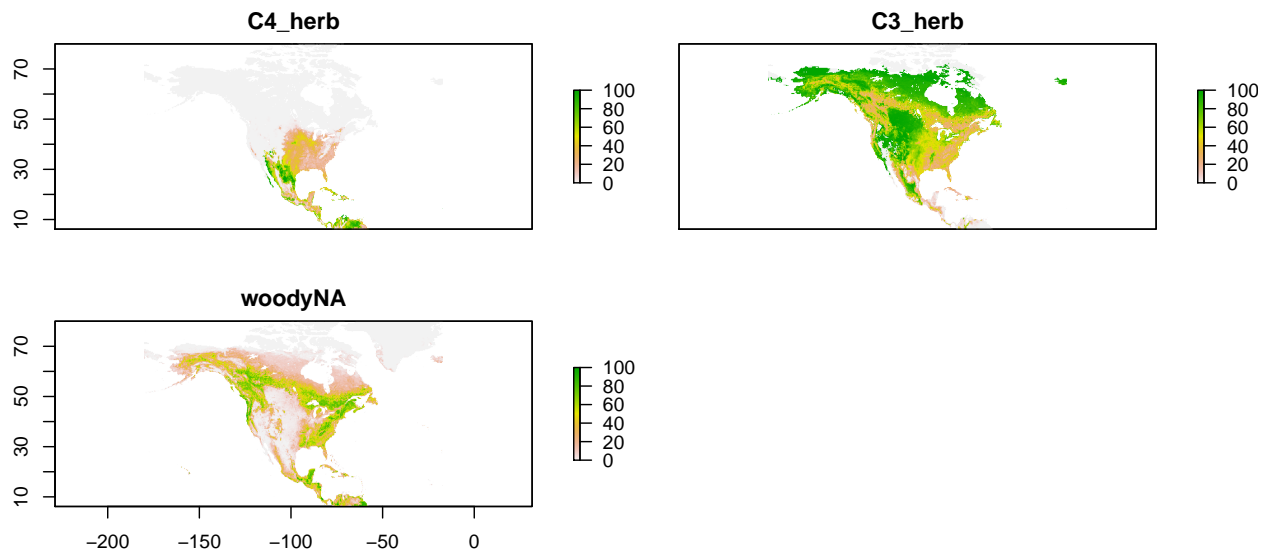
```
# Create raster stack of other (non-grassy) vegetation layers
veg_layers <- stack(woody, C3crop, C4crop)

# Indicate layers that correspond to C4 vegetation
C4_flag <- c(0, 0, 1)

# Indicate layers that correspond to herbaceous vegetation
herb_flag <- c(0, 1, 1)

# Calculate plant functional type layers (C4 grass, C3 grass, woody)
pft_cover <- calcPFTCover(C4_ratio = C4_ratio,
                        GS_mask = GS_mask,
                        veg.layers = veg_layers,
                        C4_flag = C4_flag,
                        herb_flag = herb_flag)
```

```
plot(pft_cover)
```



## Turning our vegetation map into an isoscape

We will generate a vegetation stable carbon ( $\delta^{13}\text{C}$ ) isoscape by applying a simple linear mixing model to each grid cell. We identify (from the literature)  $\delta^{13}\text{C}$  endmember values for each plant functional type layer, then weight the isotopic endmembers by the respective percent vegetation composition (in this case,  $\text{C}_4$  herbaceous,  $\text{C}_3$  herbaceous,  $\text{C}_3$  woody).

Note that in this example, we have elected to combine the  $\text{C}_4$  and  $\text{C}_3$  crop layers with corresponding natural grass layers; however, the functions presented here could be easily adapted for custom plant cover types.

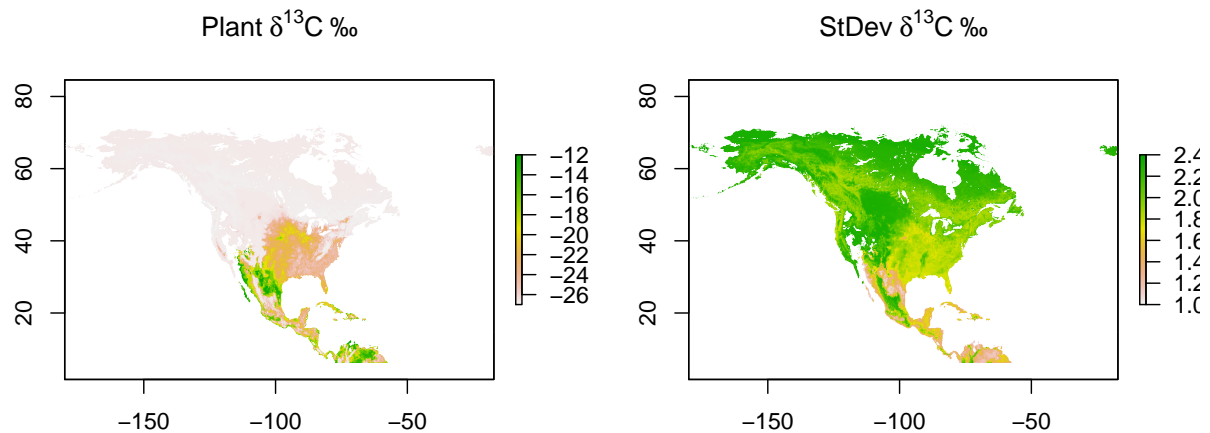
```
# d13C endmember vector for PFT layers from the literature
d13C_emb <- c(-12.5, # C4 herb
              -26.7, # C3 herb
              -27.0) # Woody

# Apply mixing model to generate d13C isoscape
d13C_iso <- calcDel13C(pft_cover, d13C_emb)

# Standard deviations of d13C endmember means from the literature
d13C_std <- c(1.1, # C4 herb
              2.3, # C3 herb
              1.7) # Woody

# Calculate weighted standard deviation of mean d13C values
d13C_iso_std <- calcDel13C(pft_cover, d13C_std)

par(mfrow = c(1,2))
plot(d13C_iso, main = expression(Plant~{\delta}^{13}\text{C}~"\u211"),
     xlab = "", ylab = "", zlim = c(-27,-12)) # Mac users: substitute "\u2030"
plot(d13C_iso_std, main = expression(StDev~{\delta}^{13}\text{C}~"\u211"),
     xlab = "", ylab = "", zlim = c(1.0, 2.4)) # Mac users: substitute "\u2030"
```



Thank you for your time, and we hope you enjoyed this test version of grassmapr!

## References

- Cerling, T. E., & Harris, J. M. (1999). Carbon isotope fractionation between diet and bioapatite in ungulate mammals and implications for ecological and paleoecological studies. *Oecologia*, 120, 347 - 363.
- Collatz, G. J., Berry, J. A., & Clark, J. S. (1998). Effects of climate and atmospheric CO<sub>2</sub> partial pressure on the global distribution of C<sub>4</sub> grasses: Present, past, and future. *Oecologia*, 114, 441 - 454.
- Diefendorf, A. F., Mueller, K. E., Wing, S. L., Koch, P. L., & Freeman, K. H. (2010). Global patterns in leaf <sup>13</sup>C discrimination and implications for studies of past and future climate. *Proceedings of the National Academy of Sciences USA*, 107, 5738 - 5743.
- Ehleringer, J. R., Cerling, T. E., & Helliker, B. R. (1997). C<sub>4</sub> photosynthesis, atmospheric CO<sub>2</sub>, and climate. *Oecologia*, 112, 285 - 299.
- Hobson, K. A. (1999). Tracing origins and migration of wildlife using stable isotopes: A review. *Oecologia*, 120, 314 - 326.
- Kohn, M. J. (2010). Carbon isotope compositions of terrestrial C<sub>3</sub> plants as indicators of (paleo) ecology and (paleo) climate. *Proceedings of the National Academy of Sciences USA*, 107, 19691 - 19695.
- Powell, R. L., Yoo, E.-H., & Still, C. J. (2012). Vegetation and soil carbon <sup>13</sup> isoscapes for South America: Integrating remote sensing and ecosystem isotope measurements. *Ecosphere*, 3, 1 - 25.
- Still, C. J., Berry, J. A., Collatz, G. J., & DeFries, R. S. (2003). Global distribution of C<sub>3</sub> and C<sub>4</sub> vegetation: Carbon cycle implications. *Global Biogeochemical Cycles*, 17, 1006.