PaleolithicGreening

Supplement for the publication: **Where the grass is greener: Estimated vegetation periods and their explanatory potential for site distribution in the East European Plain**

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Description:

> Our study relies on the following work routine. This supplement is written in R. One of our primary goals is to perform all functions provided. The documentation and the complete workflow are published. All consecutive analyses can follow the exemplary procedure. This script contains the main functionality of our research, in which all parameters needed for conducting the functions used in scripts, libraries and packages are introduced. Our project is reproducible, which is easily done by running the following script (main.R).

Variables

parameter : LGM, Black Sea, NGRIP

LGM : base data file

period : GS-3, GI-3, GS-4, GI-4, GS-5.1, GI-5.1, GS-5.2, GI-5.2, GS-6, GI-6, GS-7, GI-7, GS-8, GI-8, GS-9, GI-9

month : 1 through 12 (1:12)

step_day_size : 2, 7, 14, 21, 28

step_list : 20, 60, 47.5, 65, 2.5

df_result_result : create new data frame

Details

As one of the most important variables to distinguish, the three different data files (LGM, Black Sea, NGRIP) are listed in the classification **parameter**.

The base data file is assigned to **LGM** from which all subsequent results stem.

There are 16 different time periods, eight stadial and eight interstadial periods (GS-3, GI-3, GS-4, GI-4, GS-5.1, GI-5.1, GS-5.2, GI-5.2, GS-6, GI-6, GS-7, GI-7, GS-8, GI-8, GS-9, GI-9), which are assigned to **period**.

The parameter **month** is assigned with the number of months of a year, to show the change in temperature over the period of a year.

To show the transition of the vegetation period and temperature over an area in a time frame, the parameter **step_day_size** (2,7,14,21,28) is used.

To define and edit the coordinates as well as the distance between the coordinate points, the parameter **step_list** (20, 60, 47.5, 65, 2.5) is used. Latidute south to north: 47.5 to 65, longitude west to east: 20 to 60, distance: 2.5

df_result_result creates a data frame to build a new and better table, filtering the vegetation period table results.

Folder structure and contents

> this folder structure has been built to clearly structure the data input and the results that are generated through this script.

- Base Data:

    - VegPer_Base_Data/LGM_Base_Data.csv
    - VegPer_Base_Data/Period_BlackSea.csv
    - VegPer_Base_Data/Period_NGRIP.csv
    - VegPer_Base_Data/QGIS_ID_File.csv
    - VegPer_Base_Data/QGIS_ID_File.xlsx

- QGIS

    - pycache (Folder)
    - exdata (Folder)
    - froot_loops_layout_temp.qpt
    - Froot_Loops_QGIS_3_layout.qgz
    - geographical_data (Folder)
    - layout_data (Folder)
    - link_node_data (Folder)
    - links (Folder)
    - python_scripts (Folder)
    - rasterfiles (Folder)
    - sites (Folder)
    - VegPer_layout.qgz

- Scripts

    - main.R
    - Calc21Day.R
    - CalcStepsStandardised.R
    - CalcFilter.R
    - plot_2x2.R

- Result Folder Structure

    - VegPer_Results/21Day_BlackSea_Results

Code

main.R

```r
#libraries

library(tidyverse)
library(dplyr)
library(purrr)

# links to the required R scripts
setwd(dirname(rstudioapi::getSourceEditorContext()$path))
source("../VegPer_R_Scripts/Calc21Day.R")
source("../VegPer_R_Scripts/CalcStepsStandardised.R")
source("../VegPer_R_Scripts/CalcFilter.R")
source("../VegPer_R_Scripts/plot_2x2.R")

# set workspace
setwd("../") #reference inside of the github / working directory folder

# global parameter:
parameter <- c("BlackSea" ,"NGRIP", "LGM") #name of the period data sets

# create new directories and folders for the results
for (p in parameter){
  dir.create(file.path(paste0('VegPer_Results/')),
  showWarnings = FALSE)
  dir.create(file.path(paste0('VegPer_Results/Calc_Step_Results/Calc_Step_',p)),
  showWarnings = FALSE)
  dir.create(file.path(paste0('VegPer_Results/21Day_',p,'_Results')),
  showWarnings = FALSE)
  dir.create(file.path(paste0('VegPer_Results/Filter_Results')),
  showWarnings = FALSE)
```

```r
  dir.create(file.path(paste0('VegPer_Results/Filter_Results/Filter_Results_',p)),
  showWarnings = FALSE)

dir.create(file.path(paste0('VegPer_Results/Filter_Results/Filter_Results_',p,'/no
des')),
  showWarnings = FALSE)
}

# input files
# LGM base data that will be used to add factors to get the temperature data of
stadial and interstadial periods
LGM <- read.csv("VegPer_Base_Data/LGM_base_data.csv", header = T,
fileEncoding="UTF-8-BOM")

# list of stadial and interstadial climatic periods of interest:
period <- c("GS-3", "GI-3", "GS-4", "GI-4", "GS-5.1", "GI-5.1", "GS-5.2", "GI-
5.2", "GS-6", "GI-6", "GS-7", "GI-7", "GS-8", "GI-8", "GS-9", "GI-9")


### Calc21Day.R

# list of months
month <- c(1:12)

# function to calculate the 21 day average of all periods and data sets
lapply(parameter,DAY_21,period,month)


### CalcStepsStandardised.R

# list of parameters needed for the step-function:
step_day_size <- c(2,7,14,21,28)

# list of coordinates:
step_list <- c(20, 60, 47.5, 65, 2.5)

# set workspace and folders for results
setwd("VegPer_Results/")

# function to calculate the steps between each coordinate node of all periods and
data sets:
lapply (parameter,stepfunction,period,step_day_size)


### CalcFilter.R

setwd("../")
setwd("VegPer_Results/")

df_result_result <- data.frame()

# function to filter the calculated results of all periods and data sets:
lapply (parameter,VegPer_Results,period,df_result_result)
```

```
#### create the plots with Python and QGIS ####


### plot_2x2

period_concat <- list(list("GS-3", "GI-3"),list("GS-4", "GI-4"), list("GS-5.1",
  "GI-5.1"),list("GS-5.2", "GI-5.2"), list("GS-6", "GI-6"),list("GS-7", "GI-7"),
  list("GS-8", "GI-8"), list("GS-9", "GI-9"))


setwd("extdata")
lapply (parameter,plot_2x2,period_concat)


### Python ###

library(reticulate)
use_python("C:/Program Files/QGIS 3.10/apps/Python37")
#C:\Program Files\GDAL
Sys.setenv(RETICULATE_PYTHON = "C:/Program Files/QGIS 3.10/apps/Python37")
getwd()
setwd("VegPer_QGIS/")
reticulate::py_discover_config(required_module = "gdal")
source_python("Froot_Loops_QGIS_3.py")
```

Calc21Day.R

> The base temperature LGM (last glacial maximum) data is used to calculate the vegetation period during the LGM and between stadial periods (GS-3 until GS-9) as well as interstadial periods (GI-3 until GI-9). Two different period correction factor tables are used, which calculate the vegetation period with NGRIP data and with Black Sea data in the LGM and stadial/interstadial periods. The temperature data is then filtered to display the vegetation period of each time period. First the mean of 3 temperatures has to be equal or above 5 degrees Celsius. The temperature data is then filtered and shows each day, that has a mean temperature >= 5 °C. The vegetation period start and end is defined as 21 consecutive days with a mean temperature of equal or above 5 degrees Celsius. The new temperature data is filtered and shows the start and end of the vegetation periods for every time period.

Calc21Day Functions

calc_21

period_correction

Day_21

Details Calc21Day Functions

The function Day_21 sets up the basic calculation and code for the vegetation period data. The base LGM (last glacial maximum) data shows the temperature each day of the year (*Temp*) as well as the mean temperature in another column (*Temp_mean*). This file is imported and renamed **LGM_temp** to work with and and change the file, without corrupting the main data file. The function Day_21 sets up the calculation of the base LGM data first, to have **LGM_temp** run through the calc_21 function and afterwards use the calculated Vegetation data for LGM to then add the season factors (period_correction function) to calculate the vegetation periods for the defined interstadial and stadial time periods.

With calc_21 the start and end of the vegetation period is calculated. We have set the start and end of the vegetation period as 21 days of consecutive temperatures above 5 degrees Celsius. calc_21 uses two subsets which define if the mean temperature was above or below 5 degrees Celsius for 21 consecutive days before or after the currently checked Day of Year. The function runs trough the column *Veg* of the sorted data (LGM_temp) and shows the vegetation period of a temperature mean of 5 degrees Celsius for at least 21 consecutive days by depicting either a 1 (if at least 21 consecutive days) or 0 (if less than 21 consecutive days) in the column *Veg.21Day*.

The function period_correction uses the base data (LGM), which has the calculated mean temperature, and sorts the data to show if the mean temperature is above or below 5 degrees Celsius. It is sorted by depicting either a 1 (if temperature is over 5 degrees) or 0 (if temperature is below 5 degrees) into the column *Veg*. The function also adds the period correction factor data (period_correction) from NGRIP and Black Sea to the base data (LGM). Afterwards the calc_21 function is used to sort and show the vegetation period of the new data with the added season factors.

```
# generate the vegetation period for LGM

calc_21 <- function (LGM_temp) {
 i = 1
 while (i < nrow(LGM_temp)){ # all rows will be calculated (1-49640)

  if(LGM_temp[i,]$Temp_mean >= 5){
   LGM_temp[i,]$Veg = 1
  }else {
   LGM_temp[i,]$Veg = 0
  }

  test1 <- subset(LGM_temp, ID >= i & ID < i+21)
  test2 <- subset(LGM_temp, ID <= i & ID > i-21)

  if(sum(test1$Veg == 1) == 21 || sum(test2$Veg == 1) == 21){
   LGM_temp[i,]$Veg.21Day = 1
  }else { #
   LGM_temp[i,]$Veg.21Day = 0
  }

  i=i + 1
 }
 return (LGM_temp)
}
```

```r
# generate new temperature data and vegetation periods for BlackSea and NGRIP

period_correction <- function (x,p,month) {

  LGM_temp <- LGM # the existing LGM data is assigned to a new object, so the
original data won't be manipulated

  LGM_temp$Period = x # the period list is assigned

  period_corr <- read.csv(paste("VegPer_Base_Data/Period_", p, ".csv", sep=""),
header =T,  check.names = F)
  a <- period_corr[period_corr[,"Time"]==x,]

  for(y in month) {
   b <- a[,paste(y)]
   LGM_temp[LGM_temp[,"Month"]==y,]$Temp = LGM_temp[LGM_temp[,"Month"]==y,]$Temp
+b
   LGM_temp[LGM_temp[,"Month"]==y,]$Temp_mean =
LGM_temp[LGM_temp[,"Month"]==y,]$Temp_mean +b
  }

  i = 1

  while (i < nrow(LGM_temp)){
   if(LGM_temp[i,]$Temp_mean >= 5){
    LGM_temp[i,]$Veg = 1
   }else {
    LGM_temp[i,]$Veg = 0
   }

   i=i + 1
  }

  # calc_21 function for the data sets for BlackSea and NGRIP

  i = 1
  while (i < nrow(LGM_temp)){

   test1 <- subset(LGM_temp, ID >= i & ID < i+21)
   test2 <- subset(LGM_temp, ID <= i & ID > i-21)


   if(sum(test1$Veg == 1) == 21 || sum(test2$Veg == 1) == 21){
    LGM_temp[i,]$Veg.21Day = 1
   }else {
    LGM_temp[i,]$Veg.21Day = 0
   }

   i=i + 1
  }

  # export path
```

```
    path <- paste("VegPer_Results/21Day_", p, "_Results/",sep="")

    # export the data in the for loop as new .csv file with the same period name as
    the period factor that was used
    write.csv(LGM_temp, paste(path, x,".csv",sep=""))
  }

  # start the function to generate new temperature data and vegetation periods for
  LGM, BlackSea and NGRIP

  DAY_21 <- function(p,period,month){
    LGM <- read.csv("VegPer_Base_Data/LGM_base_data.csv", header = T,
    fileEncoding="UTF-8-BOM")

    if (p == "LGM") {

      path <- paste("VegPer_Results/21Day_", p, "_Results/",sep="")
      LGM_temp <- LGM
      LGM_temp <- calc_21(LGM_temp)
      write.csv(LGM_temp, paste(path,'21Day_',p, ".csv",sep=""))

    }else{

      # calculate new temperature data for BlackSea and NGRIP with the
    period_correction function
      lapply(period,period_correction,p,month)
    }
  }
```

CalcStepStandardised.R

After finalising the vegetation period results, the data is divided into two main datasets – the spring/summer and the autumn/winter sets. While the spring/summer data is used to estimate pull factors towards a later greening, the autumn/winter data aims at estimating a later end of the fall. The basic rule to determine the movement is a step function, which is represented each by drawing a directed link between two nodes. The estimated begin respectively end of the vegetation period is regarded in this calculation and determines whether a link is defined. Each link is directed and can show the principle movement directory. The minimum threshold between two points is defined as two days.

CalcStepStandardised Functions

stepping

QGIS_ID

stepfunction

Details CalcStepStandardised Functions

The stepfunction seperate the LGM and BlackSea/NGRIP datasets and sets up the function stepping for LGM, NGRIP and BlackSea, with the *step_day_size* (2,7,14,21,28).

The function stepping calculates the vegetation change and the route of transmission of the fauna migration in spring and autumn, by seperating the data into to sets: spring/summer and fall/winter. It will calculate the amount of days between coordinate nodes and vegetation period starts end ends.

To define the coordinate nodes and step directions for the images in QGIS the function QGIS_ID sets up the calculation for ID points.

```r
# calculate the vegetation change and the route of transmission in spring and
autumn

stepping <- function  (csv_file, long_bottom, long_top, lati_west, lati_east,
step,step_day_size,p){

  tbl <-
    list.files(pattern = paste (csv_file,".csv", sep= '')) %>%
    map_df(~read_csv(.))


  # the for loop starts with the set up of the stadial or interstadial that is
calculated

  temp_data <- tbl

  #long_bottom = 20, long_top = 60, lati_west = 47.5, lati_east = 65, step = 2.5
  #lat_bottom = 47.5, lat_top = 65, long_west = 20, long_east = 60, step = 2.5

  VegPeriod_complete <- tbl[tbl$Veg.21Day == 1,]
  df_result <- data.frame(c("a","b","c","d","e","f","g","h"))
  df_result_max <- data.frame(c("a","b","c","d","e","f","g","h"))

  text =''

  # calculation of the min, max, sum and mean of DOY and sum of temperatures

  for (long in seq(from = long_bottom, to = long_top, step)){ # runs through every
longitude

    #calculation of the vegetation change and the route of transmission of the
fauna

    # migration in spring
    for (lat in seq(from = lati_west, to = lati_east, step)){ # runs through every
latitude
      result <- VegPeriod_complete[VegPeriod_complete$Long == long &
VegPeriod_complete$Lat == lat,] #filtering point
        data <- min(result$DOY, na.rm=T)
        for (xlong in seq(from = -step, to = step, step)){
```

```r
      for (ylati in seq(from = 0, to = step, step)){
        for (a in step_day_size){

          test <- VegPeriod_complete[VegPeriod_complete$Long == long + xlong &
VegPeriod_complete$Lat == lat + ylati,]
          data_test <- min(test$DOY, na.rm=T)
          if (data_test == Inf){break
          } else if (data == -Inf){break
          } else if (data == 0){break
          } else if (data == data_test+1){break
          } else if (data == data_test){break
          } else if (data <= data_test-a)
            {stats <- c(long,lat,long+xlong,lat+ylati,data_test-data,a,QGIS_ID
(lat,long),QGIS_ID (lat+ ylati,long + xlong))

          } else {
            break
          }
          df_result <- cbind (df_result, stats)

        }
      }
    }

    # migration in autumn
    data_max <- max(result$DOY, na.rm=T)
    for (xlong in seq(from = -step, to = step, step)){
      for (ylati in seq(from = -step, to = 0, step)){
        for (a in step_day_size){

          test <- VegPeriod_complete[VegPeriod_complete$Long == long + xlong &
VegPeriod_complete$Lat == lat + ylati,]
          data_test_max <- max(test$DOY, na.rm=T)
          if (data_max == -Inf){ break
          } else if (data_max == Inf){break
          } else if (data_max == 0){break
          } else if (data_max == data_test_max){break
          } else if (data_max == data_test_max-1){break
          } else if (data_max <= data_test_max-a)
            {stats_max <- c(long,lat,long+xlong,lat+ylati,data_test_max-
data_max,a,QGIS_ID (lat,long),QGIS_ID (lat+ ylati,long + xlong))

          } else {
            break
          }

          df_result_max <- cbind (df_result_max, stats_max)

        }
      }
    }
  }
  if (p == "NGRIP" && csv_file == "GS-6" && lat == 65 && long == 20) {stats_max
```

```r
<- ''}
    df_result <- cbind (df_result, stats)
    df_result_max <- cbind (df_result_max, stats_max)
  }

  df_result_min <- df_result %>% t(.) %>% data.frame(.) %>% .[-c(0,1),]
  df_result_max <- df_result_max %>% t(.) %>% data.frame(.) %>% .[-c(0,1),]
  rownames(df_result_min) <- NULL
  rownames(df_result_max) <- NULL


  df_result_min [0,1] <- paste('"', df_result_min [0,1], sep ="")
  df_result_max [0,1] <- paste('"', df_result_min [0,1], sep ="")


  path <- paste("../Calc_Step_Results/Calc_Step_",p,"/",sep="")
  x = "export"

  write.csv(df_result_min, paste(path,p,'_',csv_file,"_min.csv",sep=""), row.names
= F, col.names=F)
  write.csv(df_result_max, paste(path,p,'_',csv_file,"_max.csv",sep=""), row.names
= F, col.names=F)
}

# define the coordinate nodes and step directions

QGIS_ID <- function (lat,long) {
  QGIS_ID <- read_csv('../../VegPer_Base_Data/QGIS_ID_File.csv')
  val <- paste(long,'/',lat,sep='')
  QGIS_ID$Target == val
  out <- QGIS_ID[QGIS_ID$Target == val,]$ID
  return (out)
}

# seperate the LGM and BlackSea/NGRIP datasets and sets up the function stepping

stepfunction <- function(p,period,step_day_size){

  if (p == "LGM") {
    period = "21Day_LGM"

    adress <- paste0("21Day_",p,"_Results",sep="")
    setwd(adress)
    stepping (period, step_list [1], step_list [2], step_list [3], step_list [4],
step_list [5],step_day_size,p)

  }else {

    adress <- paste0("21Day_",p,"_Results",sep="")
    setwd(adress)

    lapply(period, step_list [1], step_list [2], step_list [3], step_list [4],
step_list [5],step_day_size,p)
```

```
    setwd("../")
  }
}
```

CalcFilter.R

The data created with the R script 21Day_ containing new temperature data with the use of the different period correction factor data tables as well as the creation of Vegetation periods, is now being sorted and compacted to show the result in a clearer overview. It will also be used to create nodes, which are necessary to portray the vegetation movement in QGIS.

CalcFilter Functions

```
publication
```

```
interstadial
```

```
VegPer_Results
```

Details CalcFilter Functions

`VegPer_Results` separates the LGM file and the NGRIP/BlackSea files and sets up the calculation of the `interstadial` and `publication` script.

`publication` loops over all newly created data and filters the results of the first day of the vegetation period *Start veg. day*, the last day of the Vegetation Period *End veg. day*, the sum of days within the Vegetation Period *Veg. sum day* and the sum of the temperatures within the Vegetation Period *Sum of temperature*.
The function `publication` also creates the nodes, which are used for the stepping function (**CalcStep standardised**) and are necessary for the plotting of images in QGIS.

The function `interstadial` sets up the `publication` script and uses the filtered and compacted data to export the filtered results of each period.

```
#

publication <- function (path,tbl,inter) {

  temp_data <- tbl

  VegPeriod_complete <- tbl[tbl$Veg.21Day == 1,]

  df_result <- data.frame()
  text = p

  # creation of rows for the filtered csv file
  for (i in seq(from = 47.5, to = 65, 2.5)){ text = paste (c(text,'', i, 'Start
veg. day', 'End veg. day', 'Veg. sum days','Sum of temperature'))}
```

```
  df_result <- cbind(text)

 #creation of nodes:
 text = paste (c('','ID','DOY','LAT','LONG','MIN','QGIS_ID'))
 df_node_min <- cbind(text)
 text = paste (c('','ID','DOY','LAT','LONG','MAX','QGIS_ID'))
 df_node_max <- cbind(text)

 # calculation of the min, max, sum and mean of DOY and sum of temperature
 for (long in seq(from = 20, to = 60, 2.5)){ # runs through every longitude

  node_min = ''
  node_max = ''
  stats=''

  for (lat in seq(from = 47.5, to = 65, 2.5)){ # runs through every latitude
    result <- VegPeriod_complete[VegPeriod_complete$Long == long &
VegPeriod_complete$Lat == lat,] # filtering according to coordinates
    stats <- c(stats,'',long,min(result$DOY,
na.rm=T),max(result$DOY,na.rm=T),max(result$DOY,na.rm=T)-min(result$DOY,
na.rm=T),sum(result$Temp_mean,na.rm=T))

    #creating and merging the data with the node files
    node_min = c('',paste(long,'/',lat, sep=''),min(result$DOY,
na.rm=T),lat,long,'Min',QGIS_ID (lat,long))
    node_max = c('',paste(long,'/',lat, sep=''),max(result$DOY,
na.rm=T),lat,long,'Max',QGIS_ID (lat,long))

    df_node_min = cbind(df_node_min, node_min)
    df_node_max = cbind(df_node_max, node_max)
  }

  # preparation of the csv export (publication)
  assign(paste(long), stats)
  name <- paste(long)

  df_result <- cbind (df_result, stats)

 }

 if (inter == "GI-3"){df_result_result <- data.frame(df_result)} else
{df_result_result <- rbind(df_result_result[,],df_result[,])}


 print(paste(path,inter,".csv",sep=""))
 print(path)

 write.table(df_result, paste(path,inter,".csv",sep=""), sep=',', row.names =
FALSE, col.names = FALSE)
 write.table(df_node_min %>% t(.) %>% data.frame(.) %>% .[,-1] %>% .[.[,2] !=
'Inf',] %>% .[.[,2] != '-Inf',], paste(path,'nodes/nodes_min_',inter,".csv",
sep=""), sep=',', row.names = FALSE, col.names = FALSE)
 write.table(df_node_max %>% t(.) %>% data.frame(.) %>% .[,-1] %>% .[.[,2] !=
```

```
'Inf',] %>% .[.[,2] != '-Inf',]), paste(path,'nodes/nodes_max_',inter,".csv",
sep=""), sep=',', row.names = FALSE, col.names = FALSE)
}

# set up the publication function and export the filtered results

interstadial <- function(inter,p) {

 # export path
 path <- paste("../Filter_Results/Filter_Results_",p,"/",sep="")

 tbl <-
  list.files(pattern = paste0(inter,".csv",sep="")) %>%
  map_df(~read_csv(.))
 print(paste0(inter,".csv"))

 publication(path,tbl,inter)
}

# separate the LGM file and the NGRIP/BlackSea files and set up the functions
interstadial and publication

VegPer_Results <- function (p,period,df_result_result){

  adress <- paste0("21Day_",p,"_Results",sep="")

  setwd(adress)

  if (p == "LGM"){
    period <- list("21Day_LGM")
  }
  print(p)
  lapply(period,interstadial,p)

  setwd("../")
}
```

---

additional procedure to create plots using QGIS and Python:

…

---

additional scripts

---

plot_2x2.R

> The resulting calculations of the vegetation period in the different time periods (GS-3 to GI-9), are
> being made visible using QGIS and are now compacted in R into a better overview with 2x2 images

Variables:

period_concat : list of climatic periods of interest

plot_2x2 Functions

print2x2

plot2x2

Details plot_2x2 Functions

The function plot2x2 takes the parameters *period* and *season* and splits to either use the base data (LGM) and then use the results and then plot the images in the function print2x2 or use the data from Black Sea / NGRIP and then use print2x2 to build and export the images.

print2x2 image aspects are defined and images are placed in a two by two grid to give a better overview and easier comparison. The images are then exported with the correct names being linked from the base data.

```
# libraries for plot2x2.R

library(tidyverse)
library(dplyr)
library(purrr)
library(png)
library(gridExtra)

library(RStoolbox)

library(raster)
library(rgdal)

# plotting the spatial data including the calculated arrows to show the green wave

print2x2 <- function (period,parameter) {
  print(paste(parameter,'_',period[[1]][1],'_min.png',sep=''))
  print(paste(parameter,'_',period[[2]][1],'_min.png',sep=''))

  im1 <- stack(paste('QGIS/',parameter,'_',period[[1]][1],'_min.png',sep=''))

  im2 <- stack(paste('QGIS/',parameter,'_',period[[1]][1],'_max.png',sep=''))

  im3 <- stack(paste('QGIS/',parameter,'_',period[[2]][1],'_min.png',sep=''))

  im4 <- stack(paste('QGIS/',parameter,'_',period[[2]][1],'_max.png',sep=''))

  plot_output_png <- grid.arrange(
    ggRGB(img = im1,r=1,g=2,b=3,maxpixels = 2e+06) + ggtitle(paste(parameter,'
```

```
',period[[1]][1],' (spring)',sep='')) + xlab ("") + ylab ("") + guides(fill=FALSE)
+
    theme(axis.title=element_blank(),
        axis.text=element_blank(),
        axis.ticks=element_blank(),
        panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        panel.background = element_blank()),
  ggRGB(img = im2,r=1,g=2,b=3,maxpixels = 2e+06) + ggtitle(paste(parameter,'
',period[[1]][1],' (autumn)',sep='')) + xlab ("") + ylab ("") + guides(fill=FALSE)
+
    theme(axis.title=element_blank(),
        axis.text=element_blank(),
        axis.ticks=element_blank(),
        panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        panel.background = element_blank()),
  ggRGB(img = im3,r=1,g=2,b=3,maxpixels = 2e+06) + ggtitle(paste(parameter,'
',period[[2]][1],' (spring)',sep='')) + xlab ("") + ylab ("") + guides(fill=FALSE)
+
    theme(axis.title=element_blank(),
        axis.text=element_blank(),
        axis.ticks=element_blank(),
        panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        panel.background = element_blank()),
  ggRGB(img = im4,r=1,g=2,b=3,maxpixels = 2e+06) + ggtitle(paste(parameter,'
',period[[2]][1],' (autumn)',sep='')) + xlab ("") + ylab ("") + guides(fill=FALSE)
+
    theme(axis.title=element_blank(),
        axis.text=element_blank(),
        axis.ticks=element_blank(),
        panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        panel.background = element_blank()),
  ncol=2)

 # output as png

 plot_output <- paste('2x2/',parameter,'/',period[[1]][1],'_',period[[2]]
[1],'.png', sep='')
 ggsave(plot_output, plot_output_png, device = png(), units = c("cm"), dpi = 1200,
width=25, height=16)
 while (!is.null(dev.list()))  dev.off()
}

# start the print2x2 function to plot the QGIS images

plot_2x2 <- function(parameter,period){

 if (parameter == "LGM"){
  print2x2 (list('21Day','21Day'),parameter)
```

```
  }else{
   lapply(period,parameter,print2x2)

  }
 }
```

Notes

Please cite the use of this script as: