GAMS-R Vizualization lecture

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Presentation

Lara Aleluia Reis, Environmental engineer

- Air pollution modeling (R)
- WITCH model developer at RFF-CMCC EIEE (GAMS+R).
- More than 10 years of R experience.

Contribution

L. Drouet, author of several R packages, in particular, `gdxtools` and a GAMS extension for the code editor `Visual Code Studio`.

Purpose of the lecture

You will learn how to interface GAMS and R

Through GDX file format

To visualize data sets for the diagnostic and the analysis of GAMS models.

`Ultimate Goal`	Learn how to convey your message without words

Outline

1. How to start in R
2. `GDX`: The GAMS data exchange format
3. `gdxtools`: an `R` package to read GDX
4. R basics
5. Data visualization in `R` with `ggplot2`
6. Advanced data visualization
7. Visualization tips (for the curious)

How to Start: Requirements

`Assumes`	R, RStudio and R packages are already installed

1. Install R Here
2. Install Rstudio Here

```
We need to install the following R packages:
'data.table'
'ggplot2'
'tidyr'
'stringr'
'gdxtools'* (how to install (https://github.com/lolow/gdxtools) for the brave ;) )
```

Open RStudio and paste the following command:

```
install.packages('data.table','ggplot2','tidyr','stringr')
```

The GAMS data exchange files

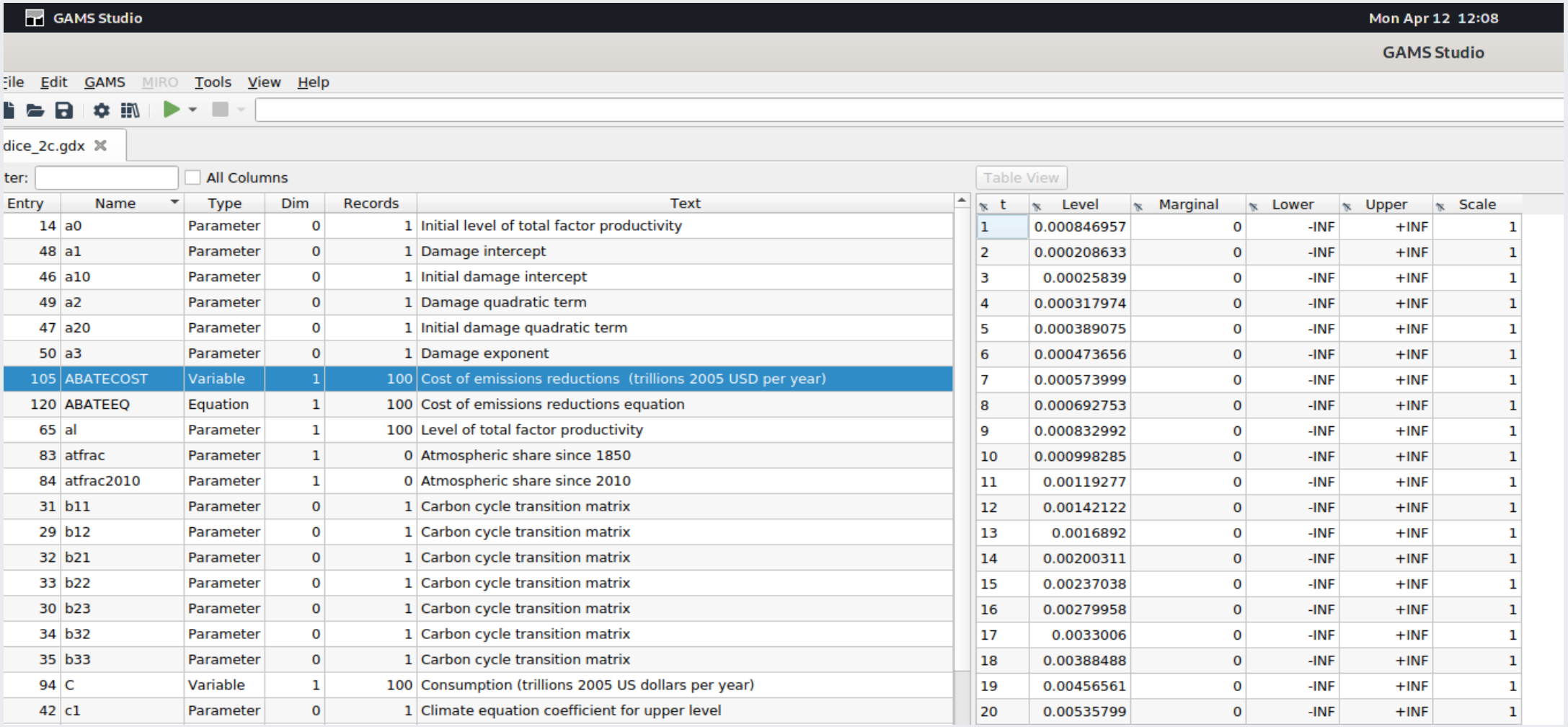
The GAMS data exchange files

The GAMS data exchange format (in short GDX) is a proprietary file format to store all elements of your GAMS programs.

- It is a database which contains a list of data from your program:
  - the sets
  - the parameters
  - the variables
  - the equations

A lot of information is stored in the GDX file. For example, for the variables, you can obtain, their values (`level`) but also their bounds (`lower`,`upper`), their marginal value (`marginal`) and scaling factors (`scale`).

Browsing a GDX in GAMS studio



Entry	Name	Type	Dim	Records	Text
14	a0	Parameter	0	1	Initial level of total factor productivity
48	a1	Parameter	0	1	Damage intercept
46	a10	Parameter	0	1	Initial damage intercept
49	a2	Parameter	0	1	Damage quadratic term
47	a20	Parameter	0	1	Initial damage quadratic term
50	a3	Parameter	0	1	Damage exponent
105	ABATECOST	Variable	1	100	Cost of emissions reductions (trillions 2005 USD per year)
120	ABATEEQ	Equation	1	100	Cost of emissions reductions equation
65	al	Parameter	1	100	Level of total factor productivity
83	atfrac	Parameter	1	0	Atmospheric share since 1850
84	atfrac2010	Parameter	1	0	Atmospheric share since 2010
31	b11	Parameter	0	1	Carbon cycle transition matrix
29	b12	Parameter	0	1	Carbon cycle transition matrix
32	b21	Parameter	0	1	Carbon cycle transition matrix
33	b22	Parameter	0	1	Carbon cycle transition matrix
30	b23	Parameter	0	1	Carbon cycle transition matrix
34	b32	Parameter	0	1	Carbon cycle transition matrix
35	b33	Parameter	0	1	Carbon cycle transition matrix
94	C	Variable	1	100	Consumption (trillions 2005 US dollars per year)
42	c1	Parameter	0	1	Climate equation coefficient for upper level

t	Level	Marginal	Lower	Upper	Scale
1	0.000846957	0	-INF	+INF	1
2	0.000208633	0	-INF	+INF	1
3	0.00025839	0	-INF	+INF	1
4	0.000317974	0	-INF	+INF	1
5	0.000389075	0	-INF	+INF	1
6	0.000473656	0	-INF	+INF	1
7	0.000573999	0	-INF	+INF	1
8	0.000692753	0	-INF	+INF	1
9	0.000832992	0	-INF	+INF	1
10	0.000998285	0	-INF	+INF	1
11	0.00119277	0	-INF	+INF	1
12	0.00142122	0	-INF	+INF	1
13	0.0016892	0	-INF	+INF	1
14	0.00200311	0	-INF	+INF	1
15	0.00237038	0	-INF	+INF	1
16	0.00279958	0	-INF	+INF	1
17	0.0033006	0	-INF	+INF	1
18	0.00388488	0	-INF	+INF	1
19	0.00456561	0	-INF	+INF	1
20	0.00535799	0	-INF	+INF	1

Writing a GDX (in GAMS)

You can write a GDX file with the command `execute_unload`:

```
execute_unload "results.gdx";
```

This will create a file containing all sets, parameters, variables and equations that are present when the line is executed.

You can also specify which elements you want to store in the GDX file:

```
execute_unload "results.gdx", VAR1, VAR2, parameter1;
```

> Some models, like WITCH, already produce automatically a GDX of their results. In that case, this step is not required.

gdxtools R Package

gdxtools

`gdxtools` is an R package which loads the content of a GDX file into R.

- It requires a GAMS installation to work.
- It is not available in the `CRAN` repository, so it needs to be installed manually.

Installation

```
if (!requireNamespace("remotes"))
  install.packages("remotes")

remotes::install_github("lolow/gdxtools")
```

You might also need to install `Rtools` to be able to install the package. See the procedure at https://cran.r-project.org/bin/windows/Rtools

Usage

Load the package

```
library(gdxtools)
```

First, `gdxtools` will try to find your `GAMS` installation. If it does not find it, add your GAMS directory in the PATH environment variable and tell the location to the library with:

```
igdx(dirname(Sys.which('gams')))
```

> Usually, when you install GAMS on Windows, it adds automatically the GAMS location to your PATH. Otherwise, follow the instructions from https://helpdeskgeek.com/windows-10/add-windows-path-environment-variable

Usage

Connexion to a GDX file

You define a GDX file with the command `gdx`. Here a results file from the WITCH model.

```
mygdx <- gdx(file.path('Material','results_ssp2_bau.gdx'))
```

`mygdx` can provide information on the GDX content.

```
print(mygdx)
```

```
## <gdx: Material/results_ssp2_bau.gdx, 2048 symbols>
```

The GDX contains *2048 symbols* (variables, parameters, sets and equations)

Usage

List of variables

```
print(mygdx$variables$name)
```

```
##  [1] "UTILITY"           "PROB"              "I"
##  [4] "K"                 "Q"                 "BAU_Q"
##  [7] "COST_Y"            "COST_EN"           "COST_FUEL"
## [10] "FPRICE"            "I_EN"              "K_EN"
## [13] "MCOST_FUEL"        "MCOST_INV"         "QEL_OUT"
## [16] "QNEL_OUT"          "Q_EN"              "Q_FUEL"
## [19] "Q_IN"              "BAU_Q_EMI"         "COST_EMI"
## [22] "CPRICE"            "Q_EMI"             "I_RD"
## [25] "K_RD"              "SPILL"             "Q_EL_FLEX"
## [28] "K_EN_GRID"         "I_EN_GRID"         "CUM_Q_CCS"
## [31] "MCOST_EMI"         "Q_CCS"             "I_EN_WINDOFF"
## [34] "I_EN_WINDON"       "K_EN_WINDOFF"      "K_EN_WINDON"
## [37] "MCOST_INV_WINDOFF" "Q_EN_WINDOFF"      "Q_EN_WINDON"
## [40] "I_EN_PV"           "I_EN_CSP"          "K_EN_PV"
## [43] "K_EN_CSP"          "Q_EN_PV"           "Q_EN_CSP"
## [46] "ADDOILCAP"         "COST_OIL"          "CUM_OIL"
## [49] "I_OIL"             "I_OUT"             "OILCAP"
```

Usage

List of parameters

```
print(mygdx$parameters$name)
```

```
##   [1] "nb_clt_infes"                "nb_clt_noopt"
##   [3] "nb_tot_infes"                "allerr"
##   [5] "allinfoiter"                 "delta_price"
##   [7] "errtrade"                    "infoiter"
##   [9] "m_consumption"               "mbalance"
##  [11] "mprofit"                     "price_iter"
##  [13] "solrep"                      "timer"
##  [15] "trust_region"                "errtol"
##  [17] "stop_nash"                   "stop_run"
##  [19] "tlen"                        "tperiod"
##  [21] "year"                        "yeoh"
##  [23] "eta"                         "gamma"
##  [25] "srtp"                        "stpf"
##  [27] "utility_cebge_global"        "utility_cebge_pc_global"
##  [29] "utility_cebge_pc_regional"   "utility_cebge_regional"
##  [31] "w_negishi"                   "alpha"
##  [33] "delta"                       "delta0"
```

Usage

List of sets

```
print(mygdx$sets$name)
```

```
##  [1] "all_feasible"
##  [2] "all_optimal"
##  [3] "irep"
##  [4] "iterrep"
##  [5] "tcheck"
##  [6] "ierr"
##  [7] "siter"
##  [8] "conf"
##  [9] "t"
## [10] "tfix"
## [11] "tfirst"
## [12] "tlast"
## [13] "pre"
## [14] "n"
## [15] "oecd"
## [16] "non_oecd"
## [17] "clt"
```

Usage

To get a vector of the global regions from the set `n`:

```
mygdx["n"][[1]]
```

```
##  [1] "brazil"      "canada"      "china"       "europe"      "india"
##  [6] "indonesia"   "jpnkor"      "laca"        "mena"        "mexico"
## [11] "oceania"     "sasia"       "seasia"      "southafrica" "ssa"
## [16] "te"          "usa"
```

This command extract `"n"` from the variable `mygdx`

> In a case of a set, you are only interested in the first column accessible with `[[1]]`

Usage

To get a data.frame of the parameter `wemi`:

```
head(mygdx["wemi"])
```

```
##        e  t        value
##   1: co2  1 8.555397e+00
##   2: co2  2 9.312155e+00
##   3: co2  3 1.008733e+01
##   4: co2  4 1.074177e+01
##   5: co2  5 1.142443e+01
##  ---
## 433: sf6 26 6.467846e-06
## 434: sf6 27 6.467689e-06
## 435: sf6 28 6.467630e-06
## 436: sf6 29 6.467609e-06
## 437: sf6 30 6.467601e-06
```

The parameter `wemi` has 2 dimensions the emission type `e` and the time period `t`.

Usage

The definition of the symbol can be available with its attribute `"gams"`.

```
print(attr(mygdx["wemi"],"gams"))
```

```
## [1] "World GHG emissions"
```

Usage

To get a data.frame of the variable `Q_EMI` (its level by default):

```
mygdx["Q_EMI"]
```

```
##                 e  t           n        value
##     1:        nip  1      brazil 0.000000e+00
##     2:        nip  1      canada 0.000000e+00
##     3:        nip  1       china 0.000000e+00
##     4:        nip  1      europe 0.000000e+00
##     5:        nip  1       india 0.000000e+00
##    ---
## 16826: ccs_plant 30      seasia 7.000000e-08
## 16827: ccs_plant 30 southafrica 7.000000e-08
## 16828: ccs_plant 30         ssa 4.538060e-06
## 16829: ccs_plant 30          te 9.142503e-07
## 16830: ccs_plant 30         usa 6.323520e-06
```

Usage

To load the variable's upper bound:

```
mygdx["Q_EMI",field = "up"]
```

```
##                 e  t           n value
##     1:        nip  1      brazil     0
##     2:        nip  1      canada     0
##     3:        nip  1       china     0
##     4:        nip  1      europe     0
##     5:        nip  1       india     0
##    ---
## 16826: ccs_plant 30      seasia   Inf
## 16827: ccs_plant 30 southafrica   Inf
## 16828: ccs_plant 30         ssa   Inf
## 16829: ccs_plant 30          te   Inf
## 16830: ccs_plant 30         usa   Inf
```

Usage

To load several gdx in one data.frame, use the function `batch_extract`

```
myfiles = file.path('Material',c("results_ssp2_bau.gdx","results_ssp2_ctax50.gdx"))
qemi = batch_extract("Q_EMI",files = myfiles)[[1]]
qemi
```

```
##                 e  t           n      value                                gdx
##     1:        nip  1      brazil 0.00000000    Material/results_ssp2_bau.gdx
##     2:        nip  1      canada 0.00000000    Material/results_ssp2_bau.gdx
##     3:        nip  1       china 0.00000000    Material/results_ssp2_bau.gdx
##     4:        nip  1      europe 0.00000000    Material/results_ssp2_bau.gdx
##     5:        nip  1       india 0.00000000    Material/results_ssp2_bau.gdx
##    ---
## 33707: ccs_plant 30      seasia 0.09963209 Material/results_ssp2_ctax50.gdx
## 33708: ccs_plant 30 southafrica 0.02860252 Material/results_ssp2_ctax50.gdx
## 33709: ccs_plant 30         ssa 1.07402186 Material/results_ssp2_ctax50.gdx
## 33710: ccs_plant 30          te 0.32548768 Material/results_ssp2_ctax50.gdx
## 33711: ccs_plant 30         usa 0.40049922 Material/results_ssp2_ctax50.gdx
```

R basics

Getting started

Let's load all the libraries that we need...

With RStudio open paste this code on the console

```
library('data.table')
library('ggplot2')
library('tidyr')
library('stringr')
library('gdxtools')
```

The command `library()` will load the library that contains the functions we will use

Whenever you need to know what a function does, how to used it, or know more about that function use **?** before the function (e.g. `?library()`,`?sum`)

Import data into R --- From GDX

```
# If necessary, tell where is located GAMS in you machine.
igdx(dirname(Sys.which('gams')))
```

```
#define a gdx
 dat_2c <- gdx('Material/dice_2c.gdx')

#have a look at the data
str(dat_2c)
```

```
## List of 7
##  $ filename  : chr "Material/dice_2c.gdx"
##  $ sets      :'data.frame':    6 obs. of  7 variables:
##   ..$ name    : chr [1:6] "t" "tfirst" "tlast" "tearly" ...
##   ..$ index   : int [1:6] 1 60 61 62 63 139
##   ..$ dim     : int [1:6] 1 1 1 1 1 1
##   ..$ card    : int [1:6] 100 1 1 0 0 10
##   ..$ text    : chr [1:6] "Time periods (5 years per period)" "" "" "" ...
##   ..$ doms    :List of 6
##   .. ..$ : int 0
##   .. ..$ : int 1
##   .. ..$ : int 1
##   .. ..$ : int 1
##   .. ..$ : int 1
##   .. ..$ : int 1
```

Import data into R

Import data from a csv

```
dat_2c <- fread('Material/Dice2016R-091916ap.csv',header=TRUE,skip=6)
```

```
#have a look at the data
str(dat_2c)
```

```
## Classes 'data.table' and 'data.frame':    37 obs. of  101 variables:
##  $ Year: chr  "Industrial Emissions GTCO2 per year" "Atmospheric concentration C (ppm)" "Atmospheric T
##  $ 2015: num  3.57e+01 4.00e+02 8.50e-01 1.05e+02 1.71e-03 ...
##  $ 2020: num  3.94e+01 4.18e+02 1.02 1.25e+02 2.44e-03 ...
##  $ 2025: num  4.29e+01 4.38e+02 1.19 1.47e+02 3.34e-03 ...
##  $ 2030: num  4.63e+01 4.59e+02 1.37 1.72e+02 4.42e-03 ...
##  $ 2035: num  4.96e+01 4.81e+02 1.55 1.98e+02 5.68e-03 ...
##  $ 2040: num  5.27e+01 5.04e+02 1.74 2.27e+02 7.15e-03 ...
##  $ 2045: num  5.55e+01 5.28e+02 1.93 2.59e+02 8.81e-03 ...
##  $ 2050: num  58.1671 552.36 2.1272 292.4898 0.0107 ...
##  $ 2055: num  60.5638 577.8409 2.3248 328.4835 0.0128 ...
##  $ 2060: num  62.715 604.021 2.524 366.818 0.015 ...
##  $ 2065: num  64.6149 630.7998 2.7243 407.4935 0.0175 ...
##  $ 2070: num  66.2608 658.0753 2.9249 450.5069 0.0202 ...
##  $ 2075: num  67.6516 685.7431 3.1253 495.8503 0.0231 ...
```

The basics of data handling

```
#dimensions
dim(dat_2c)
```

```
## [1]  37 101
```

```
#column names
names(dat_2c[,1:10])
```

```
##  [1] "Year" "2015" "2020" "2025" "2030" "2035" "2040" "2045" "2050" "2055"
```

```
#reformat column names
names(dat_2c)[2:dim(dat_2c)[2]] = as.character(as.numeric(names(dat_2c)[2:dim(dat_2c)[2]]) )

#have a look
names(dat_2c[,1:10])
```

```
##  [1] "Year" "2015" "2020" "2025" "2030" "2035" "2040" "2045" "2050" "2055"
```

The basics of data handling

```r
#change name of collum
setnames(dat_2c,'Year','Variable')

#Let's make a long table we will need it for plotting
mdat_2c=melt(dat_2c,id.vars = c('Variable'),variable.name='Years')
#or mdat_2c=melt(dat_2c,measure.vars = names(dat_2c)[2:(dim(dat_2c)[2])],variable.name='Years')

#let's have a look at the result
str(mdat_2c)
```

```
## Classes 'data.table' and 'data.frame':    3700 obs. of  3 variables:
##  $ Variable: chr  "Industrial Emissions GTCO2 per year" "Atmospheric concentration C (ppm)" "Atmospheri
##  $ Years   : Factor w/ 100 levels "2015","2020",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ value   : num  3.57e+01 4.00e+02 8.50e-01 1.05e+02 1.71e-03 ...
##  - attr(*, ".internal.selfref")=<externalptr>
```

Useful data handling functions for ggplot graphs

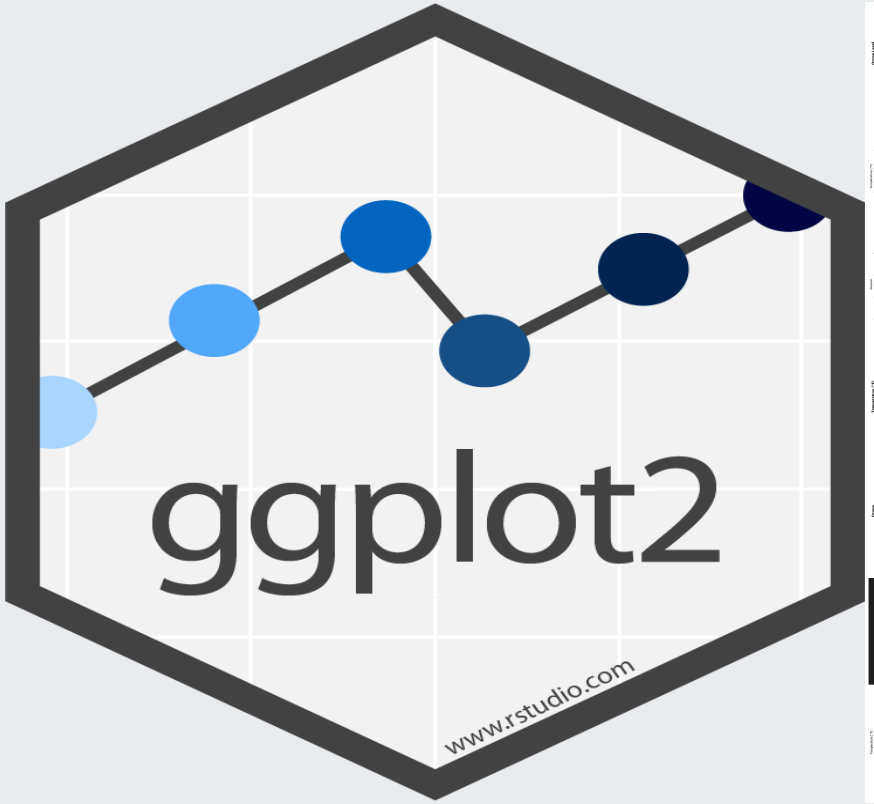
Function	Data.table	Tidyverse
From columns to row	`melt()`	`pivot_longer()`
From row to columns	`dcast()` or `spread()`	`pivot_longer()`
merge 2 data.tables	`merge()`	`full_join()`

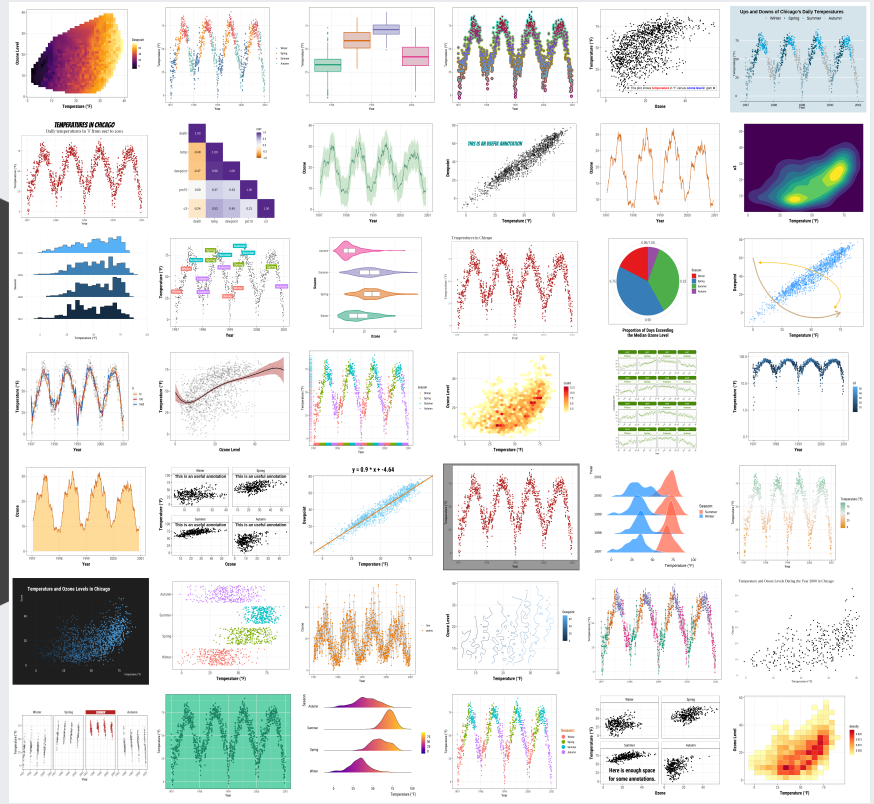
In this course we will use data.table functions, but you can use also Tidyverse functions

There are many ways of obtaining the same results.

Data visualization

The `ggplot2` package

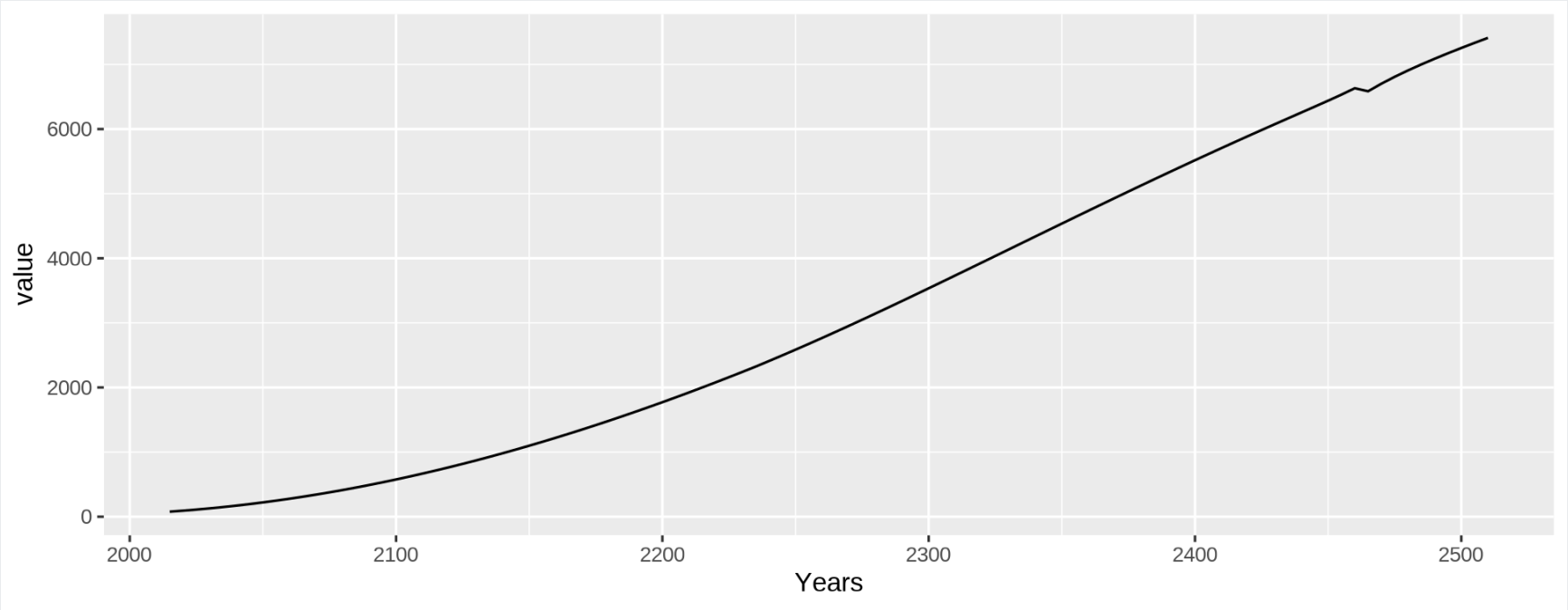




ggplot2 fast easy tips: Here

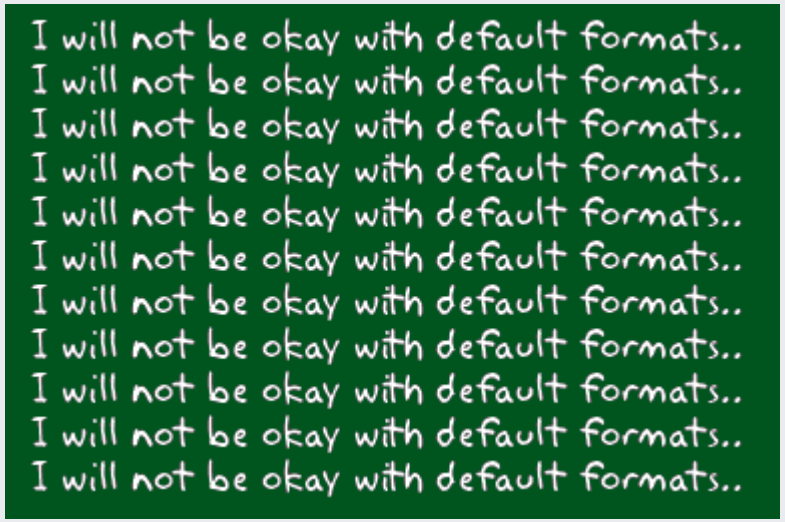
Let's make our first plot (time series)

```
#For time series we need numerical years
mdat_2c$Years=as.numeric(as.character(mdat_2c$Years))
#let's use data.table options to subset our data
ggplot(data=mdat_2c[Variable == 'Consumption'], aes(x=Years,y=value ))+
geom_line()
```



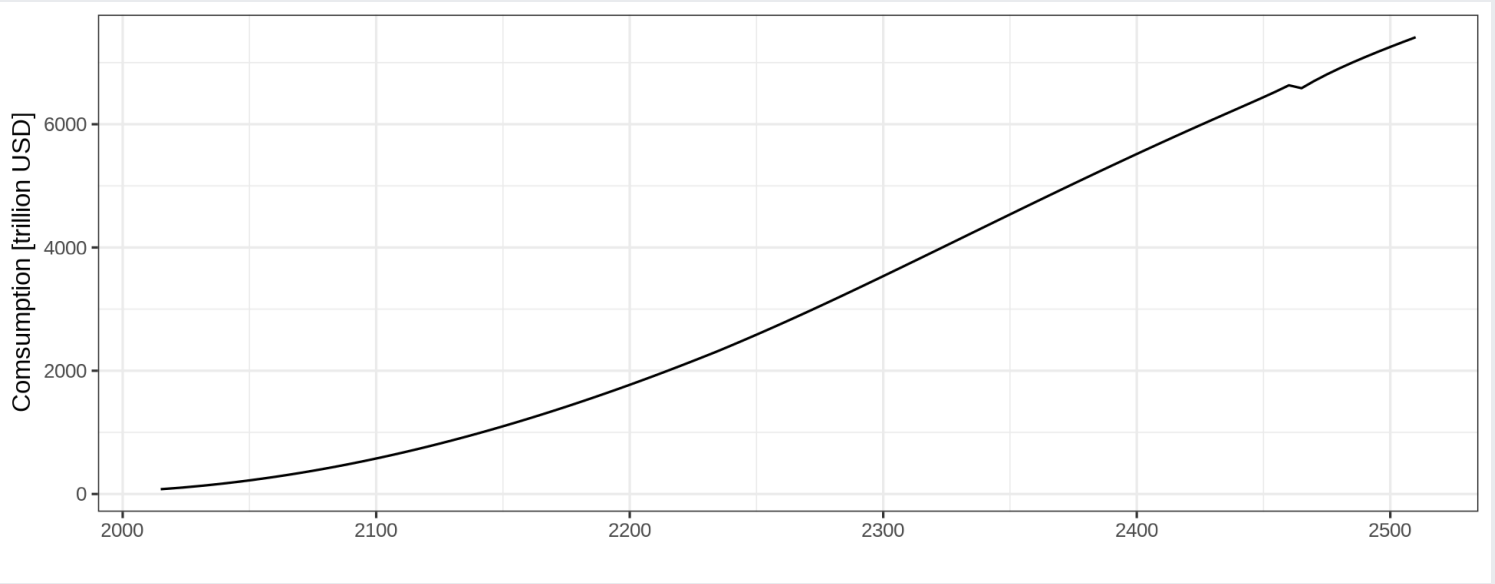
Let's make our first plot (time series)

Take time to design and format your figure



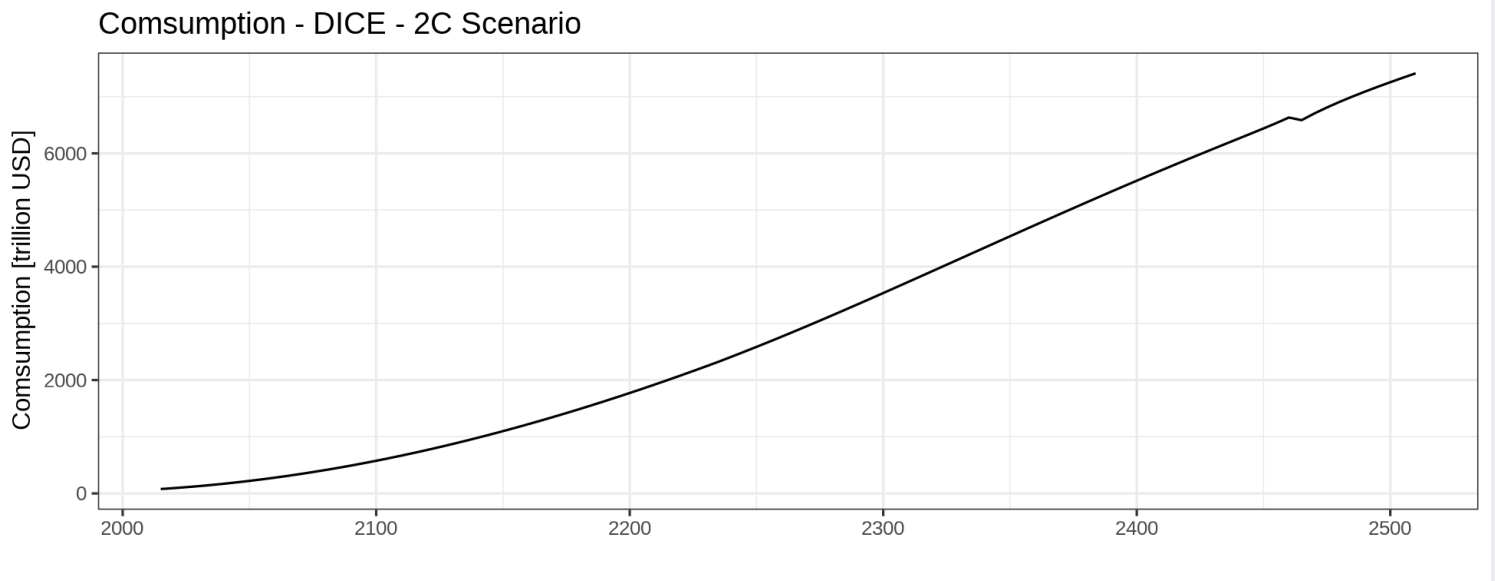
Change theme to a more sober and less noisy background

```
ggplot(data=mdat_2c[Variable == 'Consumption'], aes(x=Years,y=value ))+
geom_line() +  xlab("") + ylab('Comsumption [trillion USD]') + #add axis labels
theme_bw()
```



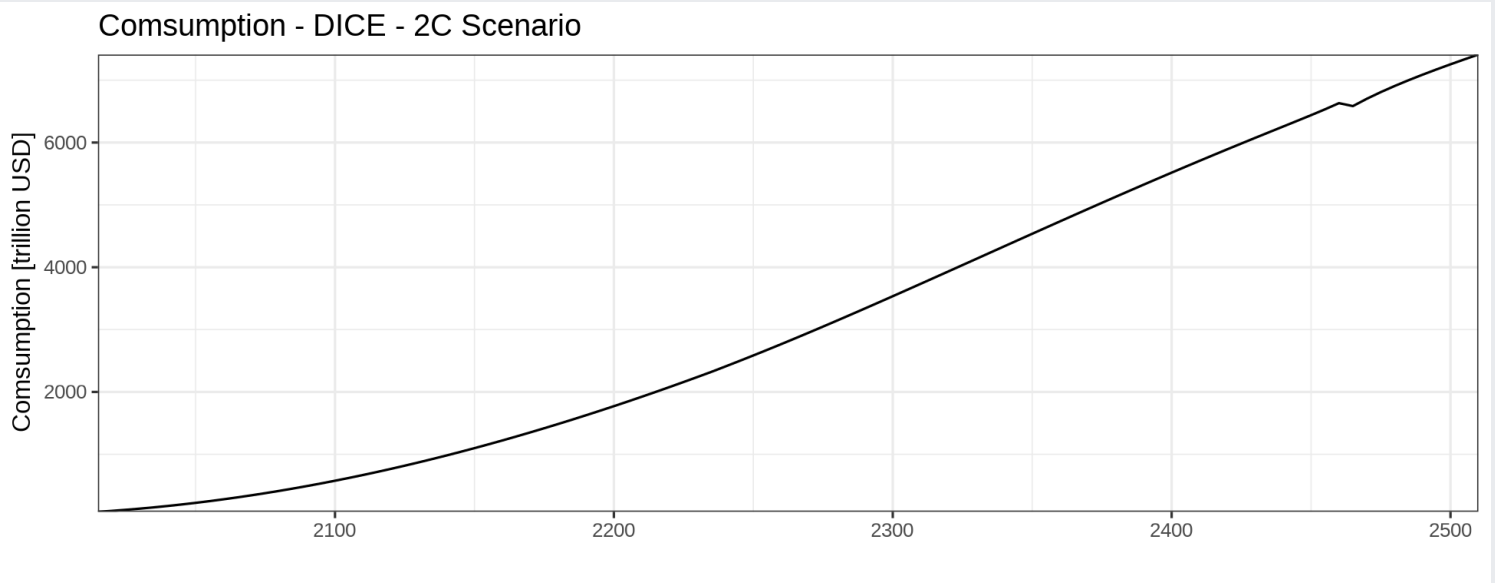
Add a title

```
ggplot(data=mdat_2c[Variable == 'Consumption'], aes(x=Years,y=value ))+
geom_line() +  xlab("") + ylab('Comsumption [trillion USD]') + #add axis labels
theme_bw() + #change theme to a more sober and less noisy background
ggtitle('Comsumption - DICE - 2C Scenario')
```



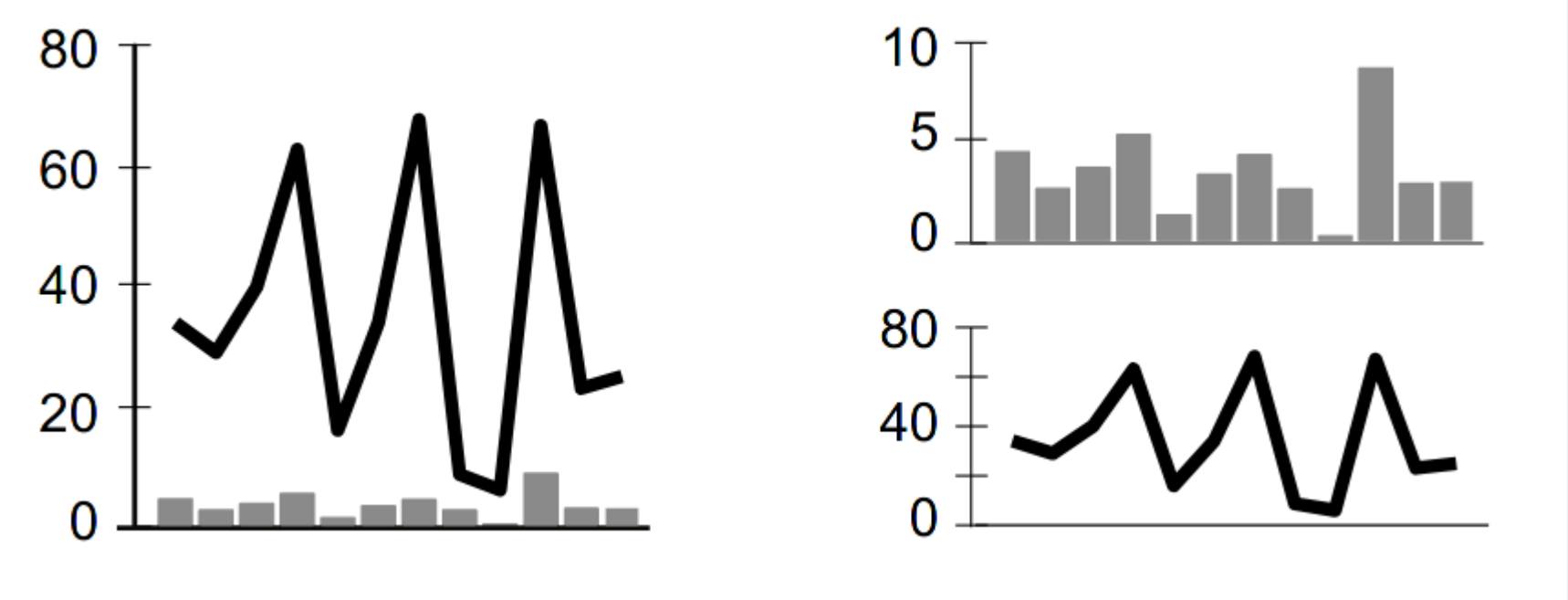
Scale the data

```
ggplot(data=mdat_2c[Variable == 'Consumption'], aes(x=Years,y=value ))+
geom_line() +  xlab("") + ylab('Comsumption [trillion USD]') + #add axis labels
theme_bw() + #change theme to a more sober and less noisy background
ggtitle('Comsumption - DICE - 2C Scenario')+ # add tittle
scale_y_continuous(expand = c(0, 0)) + #frame figure window
scale_x_continuous(expand = c(0,0))
```



Let's add more variables

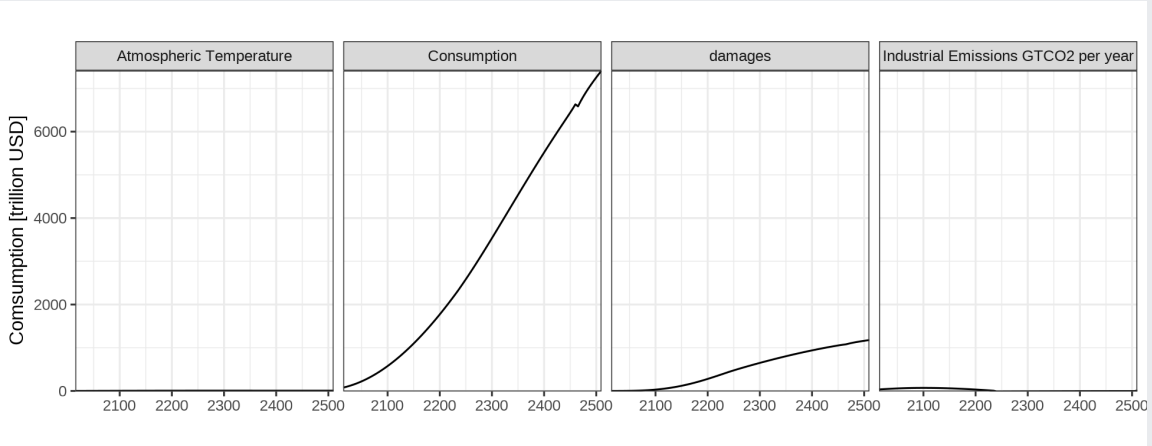
Visualization tip: Do not use different parameters in the same graph! Separate variables with large scale differences into subplots!



source: Kelleher et al. 2011

Let's add more variables

```
#again we used data.table syntax
#use c() to create a vector
vars = c('Consumption','Atmospheric Temperature',
         'Industrial Emissions GTCO2 per year',
         'damages')
ggplot(data=mdat_2c[Variable %in% vars], aes(x=Years,y=value ))+
geom_line() +  xlab("") + ylab('Comsumption [trillion USD]') + #add axis labels
theme_bw() + #change theme to a more sober and less noisy background
ggtitle(' ')+ #change add tittle
scale_y_continuous(expand = c(0, 0)) + #frame figure window to  start at 0,0
scale_x_continuous(expand = c(0,0))+
facet_wrap(~Variable,ncol=4)
```

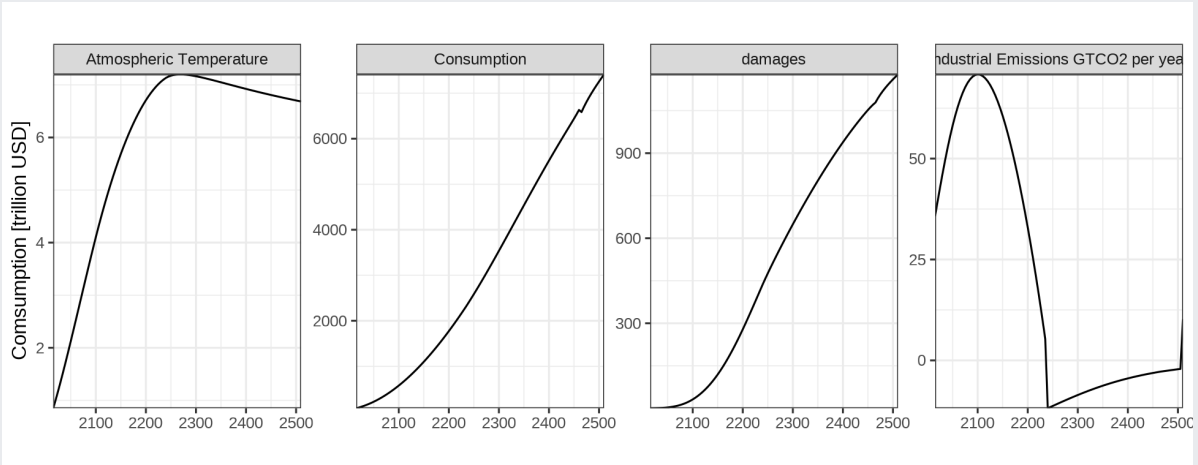


Let's add more variables --- Scale is important

What do you want to show? Magnitude or relative magnitude?

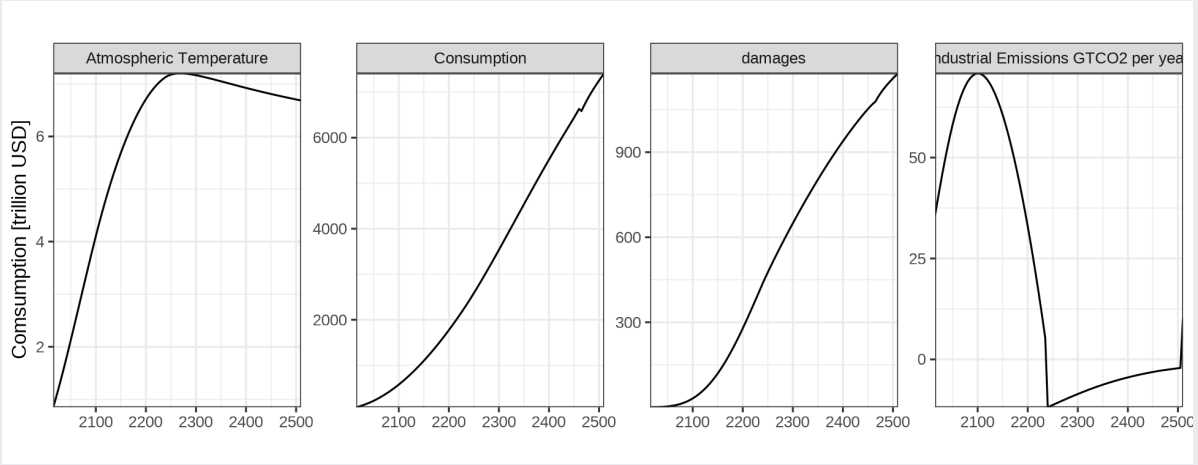
Select meaningful axis ranges depending on your purpose!

```
ggplot(data=mdat_2c[Variable %in% vars], aes(x=Years,y=value ))+
geom_line() +  xlab("") + ylab('Comsumption [trillion USD]') + #add axis labels
theme_bw() + #change theme to a more sober and less noisy background
ggtitle(' ')+ #change add tittle
scale_y_continuous(expand = c(0, 0)) + #frame figure window to  start at 0,0
scale_x_continuous(expand = c(0,0))+
facet_wrap(~Variable,ncol=4,scales='free')
```



Save your graph

```
p=ggplot(data=mdat_2c[Variable %in% vars], aes(x=Years,y=value ))+
geom_line() +  xlab("") + ylab('Comsumption [trillion USD]') +
theme_bw() +
ggtitle(' ')+
scale_y_continuous(expand = c(0, 0)) +
scale_x_continuous(expand = c(0,0))+
facet_wrap(~Variable,ncol=4,scales='free')
p
```




```
ggsave("Fig1.png",p)
ggsave("Fig1.pdf", width = 60, height = 6, units = "cm")
```

Advanced techniques

2D graphs - lines plots

First read and organize your data

```
#read several GDX (several scenarios with different carbon taxes)
myfiles = file.path("Material",c("results_ssp2_bau.gdx","results_ssp2_ctax50.gdx","results_ssp2_ctax100.gdx"))
GHG = batch_extract("Q_EMI",files=myfiles)#load GHG emissions
#have a look at the structure
str(GHG) #it is a list of a data frame
```

```
## List of 1
##  $ Q_EMI:'data.frame':    50592 obs. of  5 variables:
##   ..$ e    : chr [1:50592] "nip" "nip" "nip" "nip" ...
##   ..$ t    : chr [1:50592] "1" "1" "1" "1" ...
##   ..$ n    : chr [1:50592] "brazil" "canada" "china" "europe" ...
##   ..$ value: num [1:50592] 0 0 0 0 0 0 0 0 0 0 ...
##   ..$ gdx  : chr [1:50592] "Material/results_ssp2_bau.gdx" "Material/results_ssp2_bau.gdx" "Material/re
##   ..- attr(*, "gams")= chr ""
```

```
#this grabs the data.frame inside the list GHG$Q_EMI
#let's transform it into a data.table for easiness
GHG = setDT(GHG$Q_EMI)
#same as GHG = setDT(GHG[[1]]) or setDT(GHG[['Q_EMI']])
```

2D graphs - lines plots

First read and organize your data

```
#have a look now
str(GHG)
```

```
## Classes 'data.table' and 'data.frame':    50592 obs. of  5 variables:
##  $ e    : chr  "nip" "nip" "nip" "nip" ...
##  $ t    : chr  "1" "1" "1" "1" ...
##  $ n    : chr  "brazil" "canada" "china" "europe" ...
##  $ value: num  0 0 0 0 0 0 0 0 0 0 ...
##  $ gdx  : chr  "Material/results_ssp2_bau.gdx" "Material/results_ssp2_bau.gdx" "Material/results_ssp2_b
##  - attr(*, "gams")= chr ""
##  - attr(*, ".internal.selfref")=<externalptr>
```

```
#let's transform time periods into Years
GHG$t = as.numeric(GHG$t)*5 + 2000
#let's transform the file names into meaningful scenario names
#let's use functions of the package stringr
GHG$gdx=str_remove(GHG$gdx,'Material/results_ssp2_')
GHG$gdx=str_remove(GHG$gdx,'.gdx')
```

2D graphs - lines plots

```
# we can also change the names directly as we wish
# first let's transform into it factors
GHG$gdx=as.factor(GHG$gdx)
levels(GHG$gdx) = c('REF','Ctax100','Ctax50')
# now let's change a columns name
setnames(GHG,'gdx','Scenario')
# let's have a look again
str(GHG)
```

```
## Classes 'data.table' and 'data.frame':    50592 obs. of  5 variables:
##  $ e       : chr  "nip" "nip" "nip" "nip" ...
##  $ t       : num  2005 2005 2005 2005 2005 ...
##  $ n       : chr  "brazil" "canada" "china" "europe" ...
##  $ value   : num  0 0 0 0 0 0 0 0 0 0 ...
##  $ Scenario: Factor w/ 3 levels "REF","Ctax100",..: 1 1 1 1 1 1 1 1 1 1 ...
##  - attr(*, "gams")= chr ""
##  - attr(*, ".internal.selfref")=<externalptr>
```

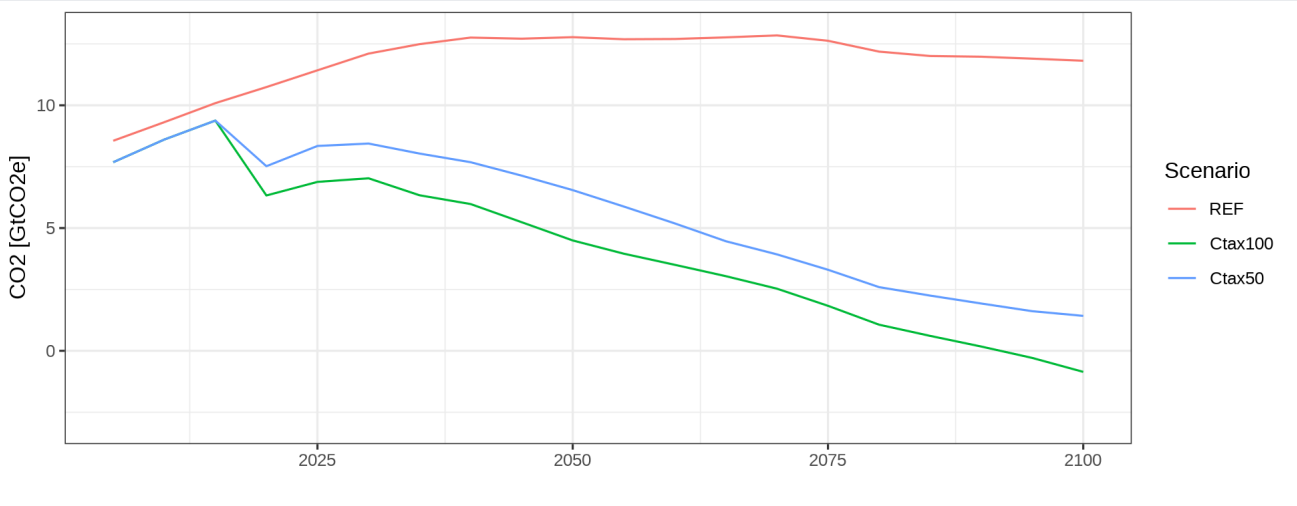
2D graphs - lines plots

```
# We have 4 changing variables, let's reduce it to 3 by aggregation the regions into world
# let's use the functionalities of data.table
wGHG = GHG[,list(value=sum(value)),by=c('e','t','Scenario')]
# have a look
str(wGHG)
```

```
## Classes 'data.table' and 'data.frame':    2976 obs. of  4 variables:
##  $ e       : chr  "nip" "nip" "nip" "nip" ...
##  $ t       : num  2005 2010 2015 2020 2025 ...
##  $ Scenario: Factor w/ 3 levels "REF","Ctax100",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ value   : num  0 0 0 0 0 0 0 0 0 0 ...
##  - attr(*, ".internal.selfref")=<externalptr>
```

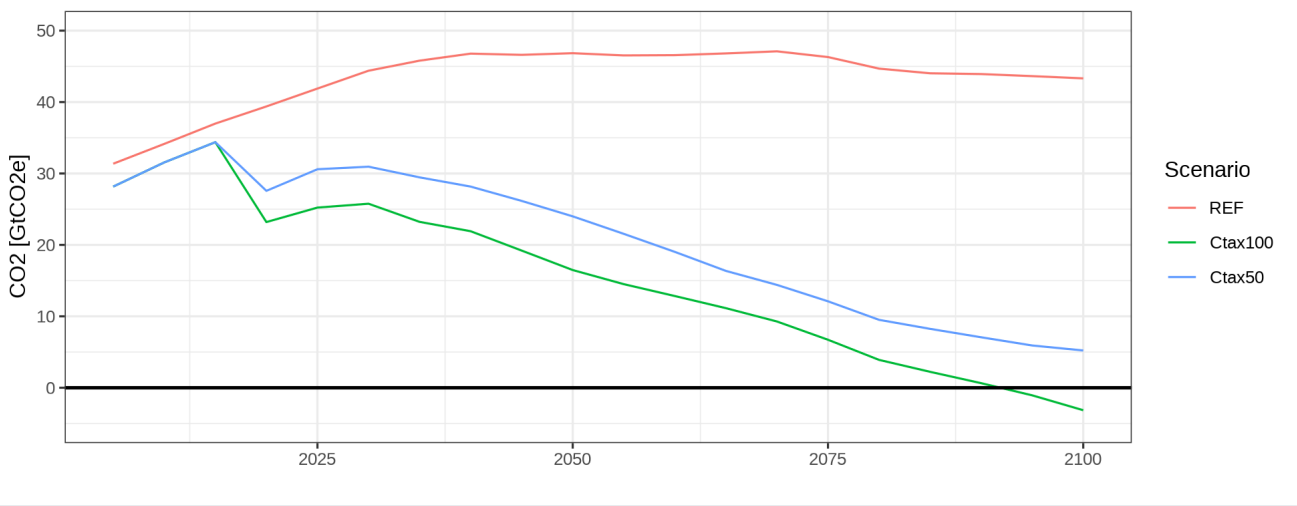
2D graphs - lines plots

```
ggplot(data=wGHG[e=='co2' & t<=2100],aes(x=t,y=value,color=Scenario))+
 geom_line() +
 theme_bw() + # change theme to a more sober and less noisy background
 scale_x_continuous(name="", limits=c(2005, 2100)) + # add title and axis limits
 scale_y_continuous(name="CO2 [GtCO2e]", limits=c(-3, 13))
```



lines plots - meaningfull meassages

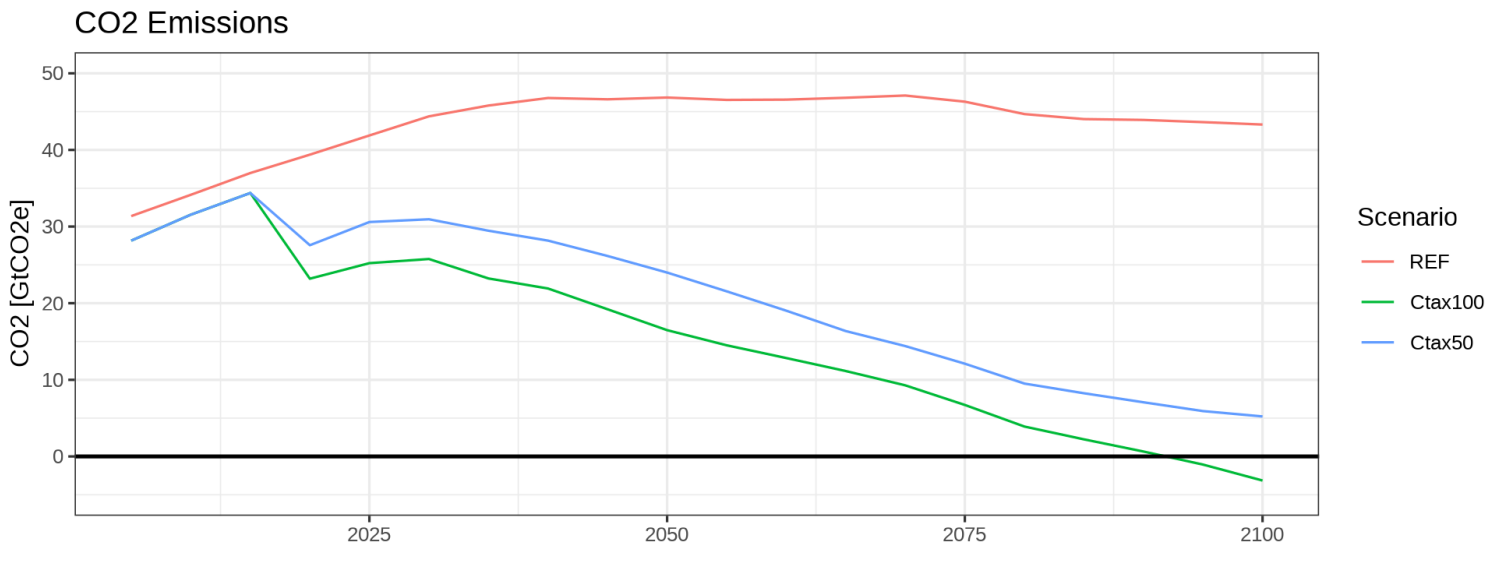
```r
# let's change unit of a given Pollutant (CO2) from GtCe to CtCO2
wGHG[e=='co2',]$value = wGHG[e=='co2',]$value*44/12
# Now let's have a look at our data
 ggplot(data = wGHG[e=='co2' & t<=2100], aes(x=t,y=value,color=Scenario))+
  geom_line() +
  theme_bw() +
  scale_x_continuous(name="", limits=c(2005, 2100)) + # add title and axis limits
  scale_y_continuous(name="CO2 [GtCO2e]", limits=c(-5, 50))+
  geom_hline(yintercept = 0,color='Black',size=0.8)
```



Now it is easy to see that a carbon tax of 100 is enough to hit negative carbon emissions

2D graphs - add a tittle

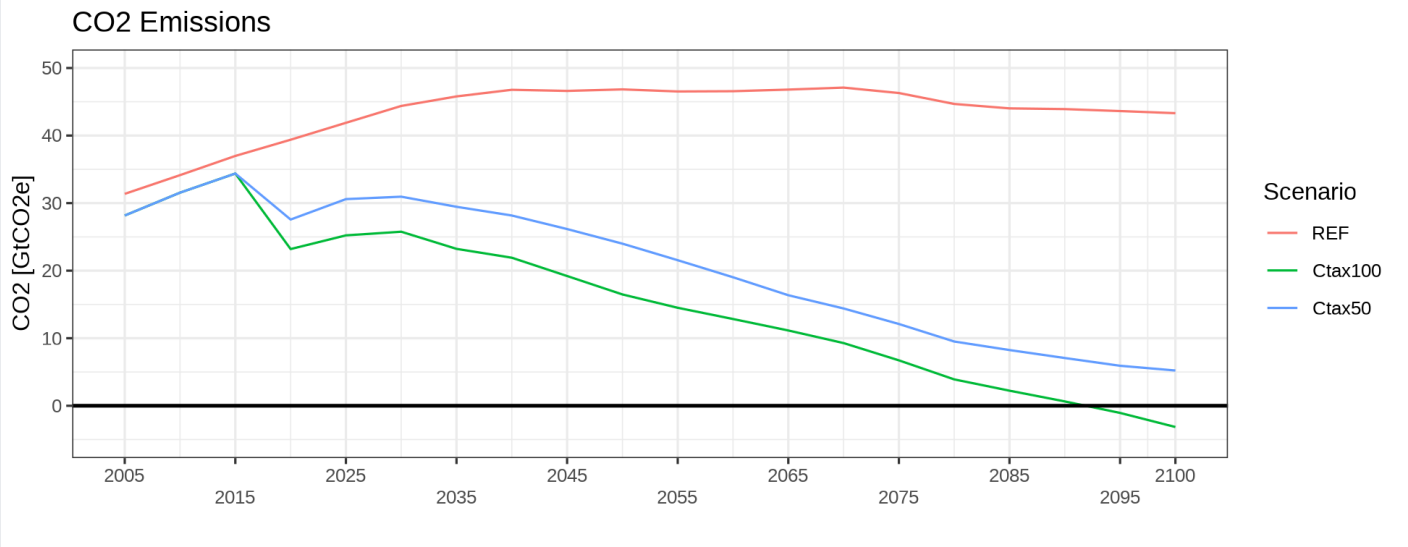
```
ggplot(data=wGHG[e=='co2' & t<=2100],aes(x=t,y=value,color=Scenario))+
 geom_line() +
 theme_bw() + # change theme to a more sober and less noisy background
 scale_x_continuous(name="", limits=c(2005, 2100)) + # add title and axis limits
 scale_y_continuous(name="CO2 [GtCO2e]", limits=c(-5, 50))+
 geom_hline(yintercept = 0,color='Black',size=0.8)+
 ggtitle('CO2 Emissions') # add title
```



2D graphs - lines plots - adjust axis

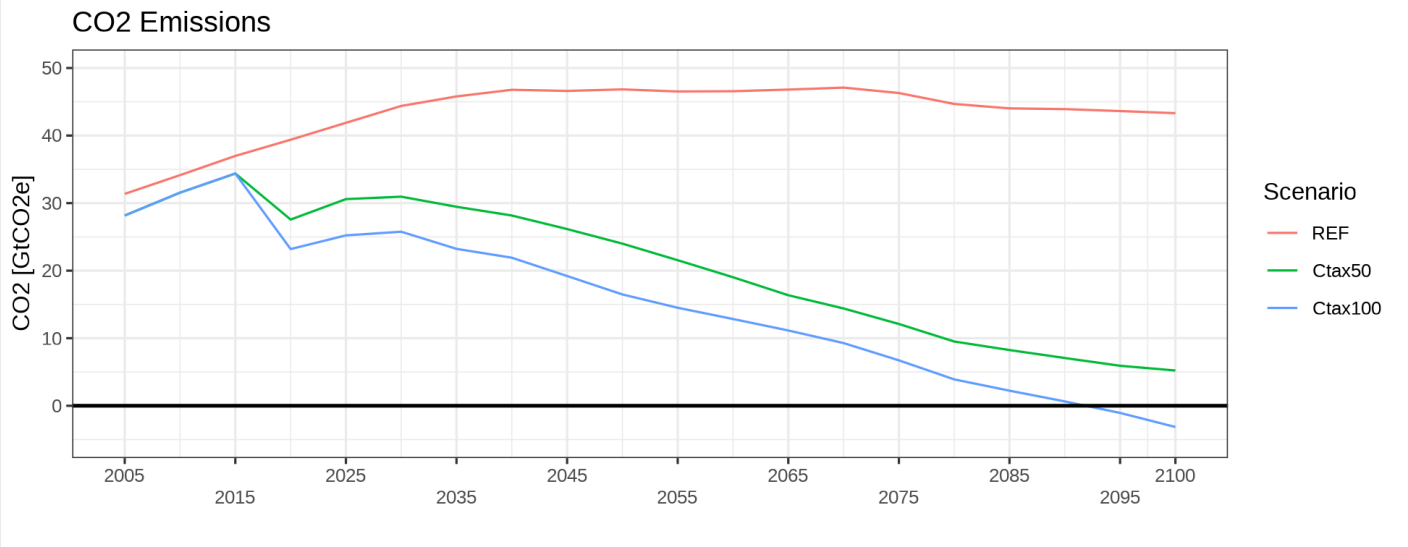
Ease the eye

```
ggplot(data=wGHG[e=='co2' & t<=2100],aes(x=t,y=value,color=Scenario))+
 geom_line() +
 theme_bw() + #change theme to a more sober and less noisy background
 scale_x_continuous(name="", limits=c(2005, 2100),# add title and axis limits
                    breaks=c(seq(2005,2100,by=10),2100), #define the axis labels
                    guide = guide_axis(n.dodge=2)) + #avoid overlaping
 scale_y_continuous(name="CO2 [GtCO2e]", limits=c(-5, 50))+
 geom_hline(yintercept = 0,color='Black',size=0.8)+
 ggtitle('CO2 Emissions') #add title
```



Help the reader

```
# change the color order to help pass your message
wGHG$Scenario <- factor(wGHG$Scenario, levels = c("REF","Ctax50","Ctax100"))
 ggplot(data=wGHG[e=='co2' & t<=2100],aes(x=t,y=value,color=Scenario))+
  geom_line() +
  theme_bw() + # change theme to a more sober and less noisy background
  scale_x_continuous(name="", limits=c(2005, 2100),# add title and axis limits
                     breaks=c(seq(2005,2100,by=10),2100), # define the axis labels
                     guide = guide_axis(n.dodge=2)) + # avoid overlapping
  scale_y_continuous(name="CO2 [GtCO2e]", limits=c(-5, 50))+
  geom_hline(yintercept = 0,color='Black',size=0.8)+
  ggtitle('CO2 Emissions') # add title
```

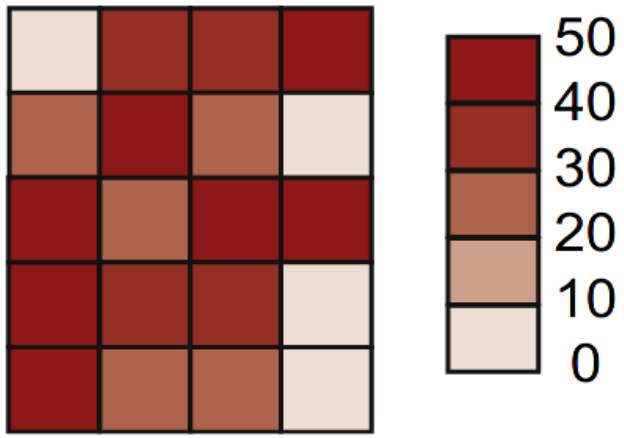


Choose your colors

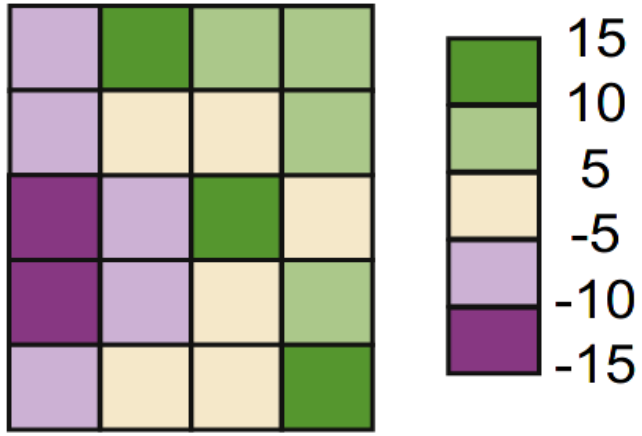
Here are some libraries with color pallets

```
#install them first if you have not yet done it
#install.packages('viridis')
library(ggsci) # scientific colors
library(viridis) #looks good and includes many options
library(RColorBrewer) # wide choice
library(wesanderson) # for the nostalgic days
```

Same magnitude



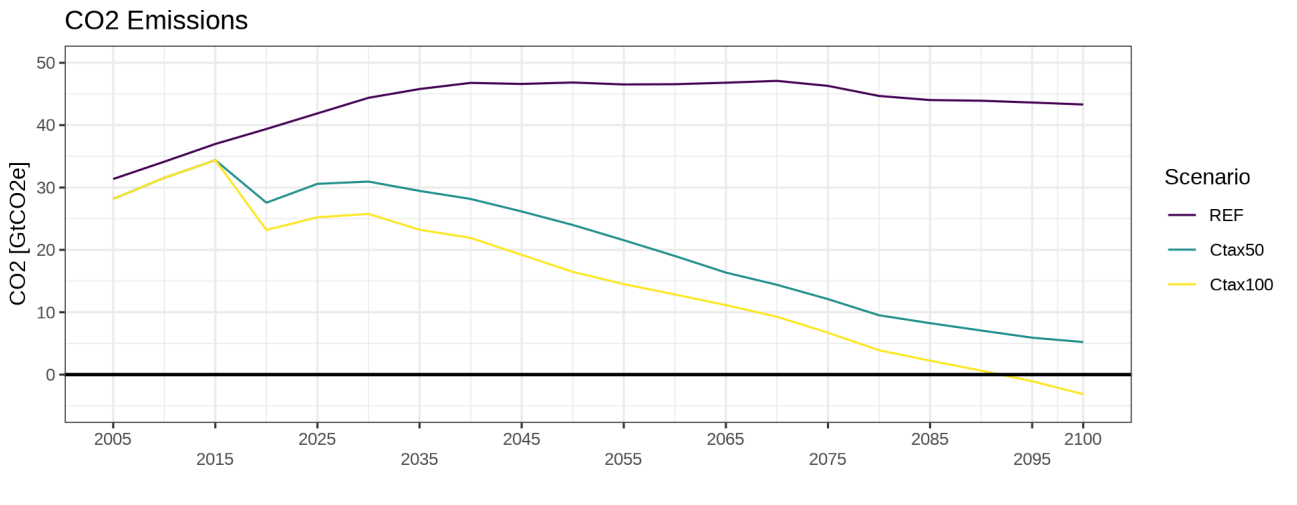
Divergent (zero in the scale)



source: Kelleher et al. 2011

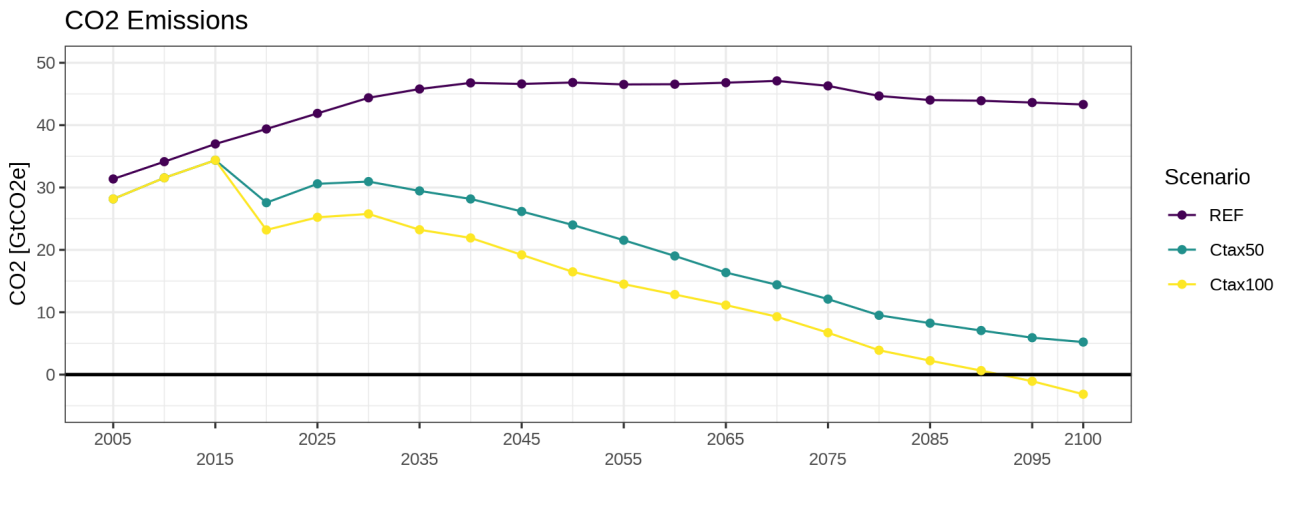
Line plot - Colors

```
# change the color order to convey help pass your message
 ggplot(data=wGHG[e=='co2' & t<=2100],aes(x=t,y=value,color=Scenario))+
  geom_line() +
  theme_bw() + # change theme to a more sober and less noisy background
  scale_x_continuous(name="", limits=c(2005, 2100),# add title and axis limits
                     breaks=c(seq(2005,2100,by=10),2100), # define the axis labels
                     guide = guide_axis(n.dodge=2)) + #avoid overlapping
  scale_y_continuous(name="CO2 [GtCO2e]", limits=c(-5, 50))+
  geom_hline(yintercept = 0,color='Black',size=0.8)+
  ggtitle('CO2 Emissions') +# add title
  scale_color_viridis(discrete = TRUE, option = "D") # use "?" to check the options
```



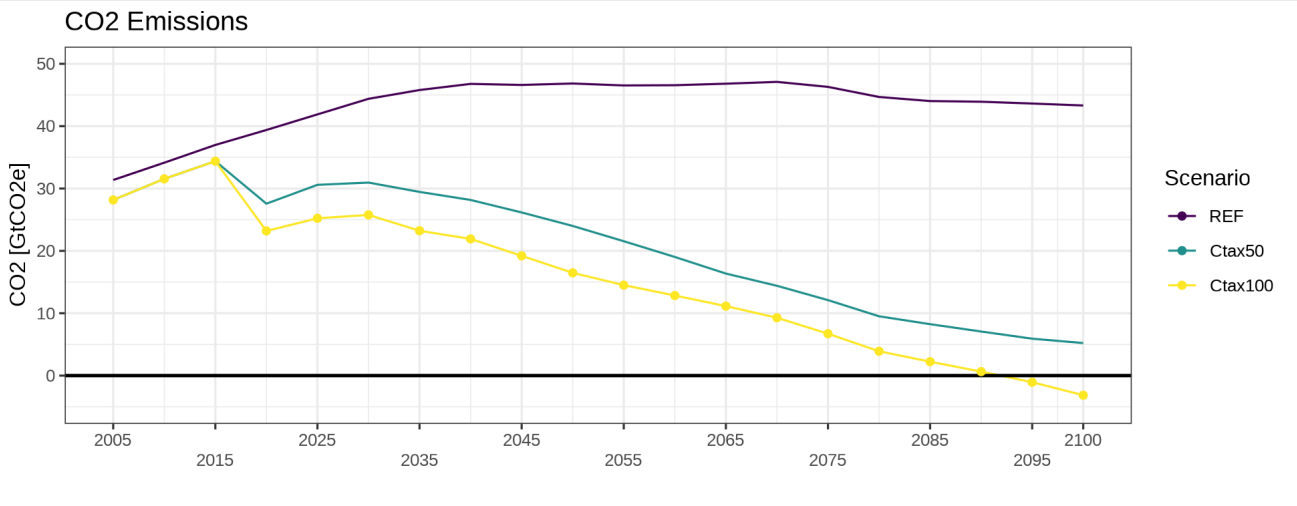
Line plot - Add points

```
ggplot(data=wGHG[e=='co2' & t<=2100],aes(x=t,y=value,color=Scenario))+
 geom_line() +
 theme_bw() + # change theme to a more sober and less noisy background
 scale_x_continuous(name="", limits=c(2005, 2100), # add title and axis limits
                    breaks=c(seq(2005,2100,by=10),2100), # define the axis labels
                    guide = guide_axis(n.dodge=2)) + # avoid overlapping
 scale_y_continuous(name="CO2 [GtCO2e]", limits=c(-5, 50))+
 geom_hline(yintercept = 0,color='Black',size=0.8)+
 ggtitle('CO2 Emissions') +#add title
 scale_color_viridis(discrete = TRUE, option = "D")+ # use "?" to check the options
 geom_point()
```



Line plot - subset differnt data

```
ggplot(data=wGHG[e=='co2' & t<=2100],aes(x=t,y=value,color=Scenario))+
 geom_line() +
 theme_bw() + # change theme to a more sober and less noisy background
 scale_x_continuous(name="", limits=c(2005, 2100),# add title and axis limits
                    breaks=c(seq(2005,2100,by=10),2100), # define the axis labels
                    guide = guide_axis(n.dodge=2)) + # avoid overlapping
 scale_y_continuous(name="CO2 [GtCO2e]", limits=c(-5, 50))+
 geom_hline(yintercept = 0,color='Black',size=0.8)+
 ggtitle('CO2 Emissions') +# add title
 scale_color_viridis(discrete = TRUE, option = "D")+ # use "?" to check the options
 geom_point(data=wGHG[e=='co2' & t<=2100 & Scenario=='Ctax100'],
            aes(x=t,y=value,color=Scenario))
```



Satter plots - load more data

Let's get another variable and merge it with our regional Emissions (GHG)

```
POP = batch_extract("l",files=myfiles) # load population
POP=setDT(POP$l)

# let's transform time periods into Years
POP$t = as.numeric(POP$t)*5 + 2000

# let's transform the file names into meaningful scenario names
POP$gdx=as.factor(POP$gdx)
levels(POP$gdx) = c('REF','Ctax100','Ctax50')
# now let's change a columns name
setnames(POP,'gdx','Scenario')
```

Scatter plots - Merging two data.table objects

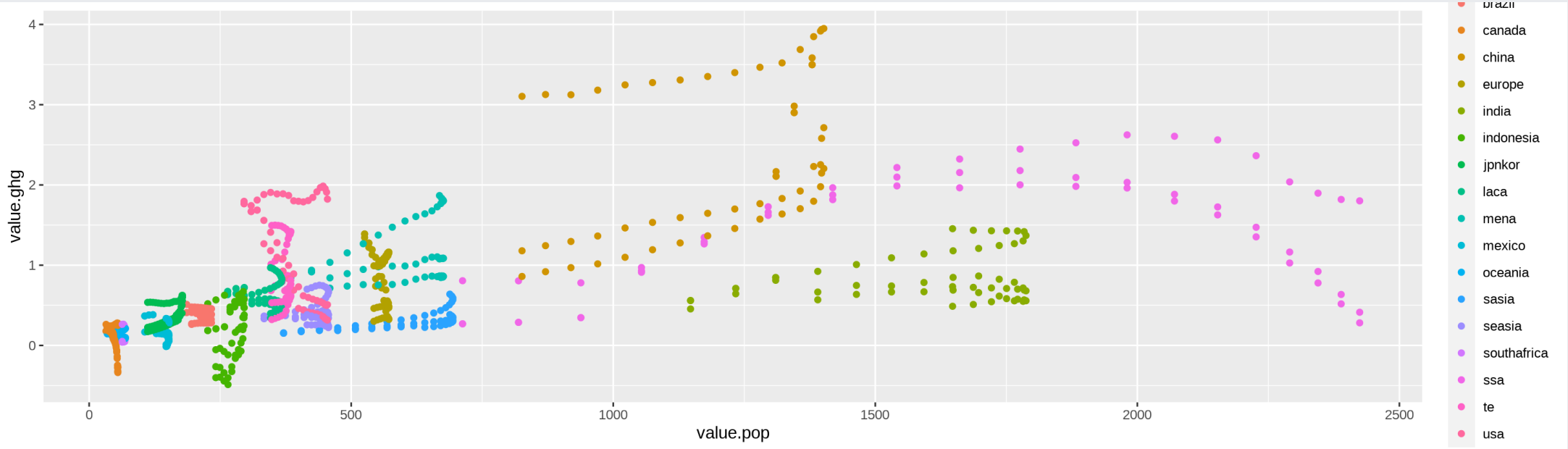
Let's get another variable and merge it with our regional Emissions (GHG)

```
# let's keep 2 emission parameters
 dat=merge(GHG[e %in% c('kghg','ccs'),],POP,by=c('t','n','Scenario'),suffixes = c(".ghg",".pop"))
 # have a look, it's magical
 str(dat)
```

```
## Classes 'data.table' and 'data.frame':    3060 obs. of  6 variables:
##  $ t        : num  2005 2005 2005 2005 2005 ...
##  $ n        : chr  "brazil" "brazil" "brazil" "brazil" ...
##  $ Scenario : Factor w/ 3 levels "REF","Ctax100",..: 1 1 2 2 3 3 1 1 2 2 ...
##  $ e        : chr  "kghg" "ccs" "kghg" "ccs" ...
##  $ value.ghg: num  5.12e-01 7.00e-08 4.10e-01 7.00e-08 4.10e-01 ...
##  $ value.pop: num  186 186 186 186 186 ...
##  - attr(*, ".internal.selfref")=<externalptr>
##  - attr(*, "sorted")= chr [1:3] "t" "n" "Scenario"
```

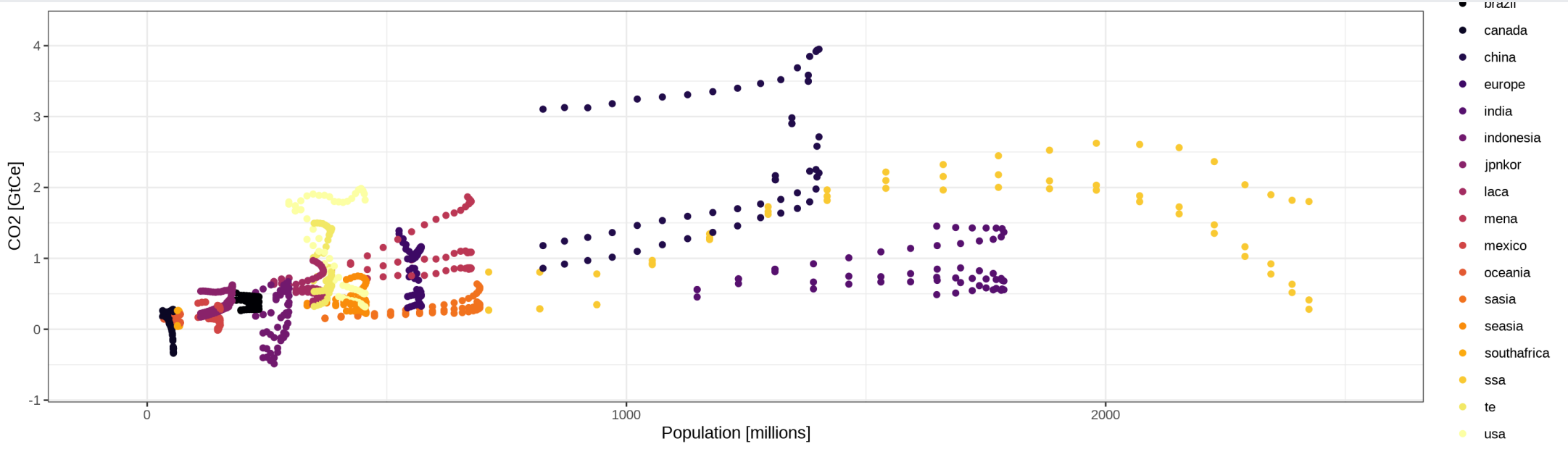
Scatter plots - Adding dimentions

```
ggplot(data=dat[t<2100 & e=='kghg'], aes(x=value.pop,y=value.ghg,color=n))+
 geom_point()
```



Scatter plots - Refuse the defaut options!

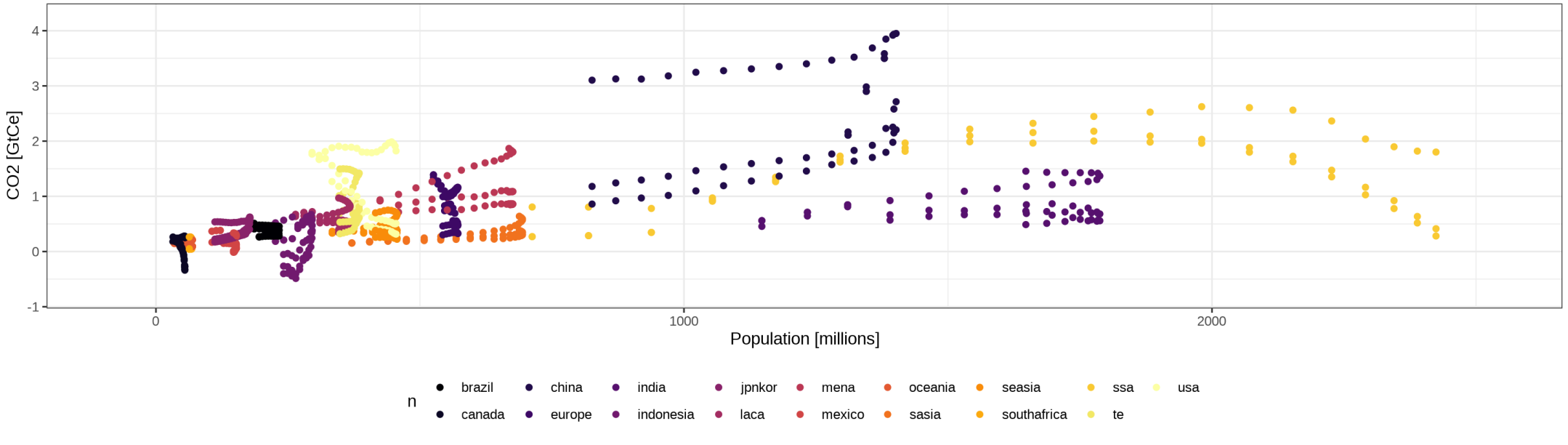
```
ggplot(data=dat[t<2100 & e=='kghg'], aes(x=value.pop,y=value.ghg,color=n))+
 geom_point() + theme_bw() +
 scale_x_continuous(name="Population [millions]",expand = c(0.1, 0.1)) +
 scale_y_continuous(name="CO2 [GtCe]",expand = c(0.1, 0.1))+
 scale_color_viridis(discrete = TRUE, option = "B") # choosing another option
```



For nice and ready to used scientific themes check the package `ggpubr`

Scatter plots - Adjust legend

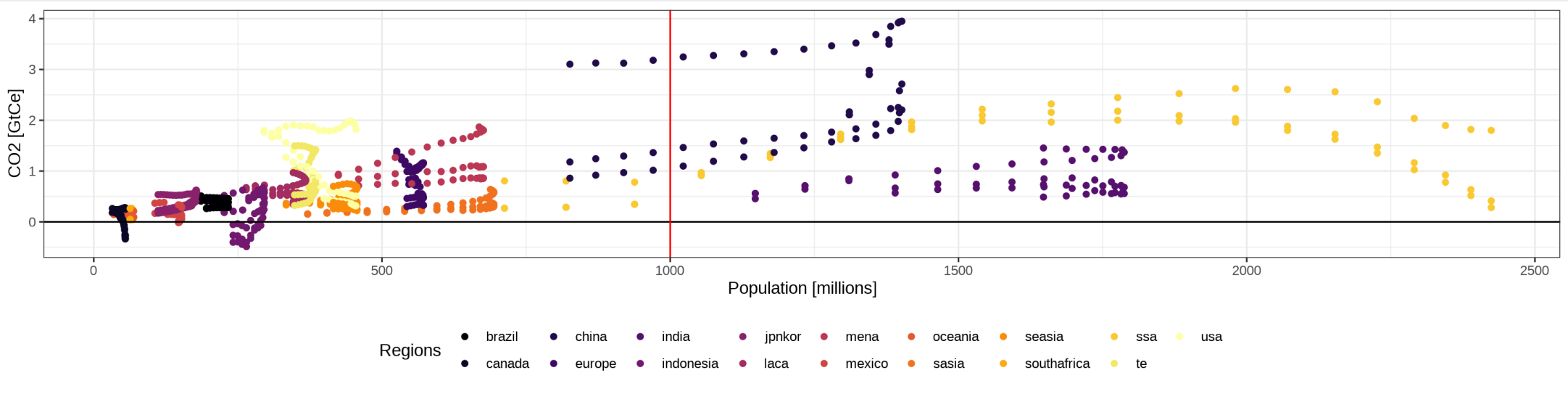
```
ggplot(data=dat[t<2100 & e=='kghg'], aes(x=value.pop,y=value.ghg,color=n))+
 geom_point() + theme_bw() +
 scale_x_continuous(name="Population [millions]",expand = c(0.1, 0.1)) +
 scale_y_continuous(name="CO2 [GtCe]",expand = c(0.1, 0.1))+
 scale_color_viridis(discrete = TRUE, option = "B")+ # choosing another option
 guides(col = guide_legend(ncol = 9))+ # divide in 9 columns
 theme(legend.position="bottom") # put on top
```



Scatter plots - Details are important

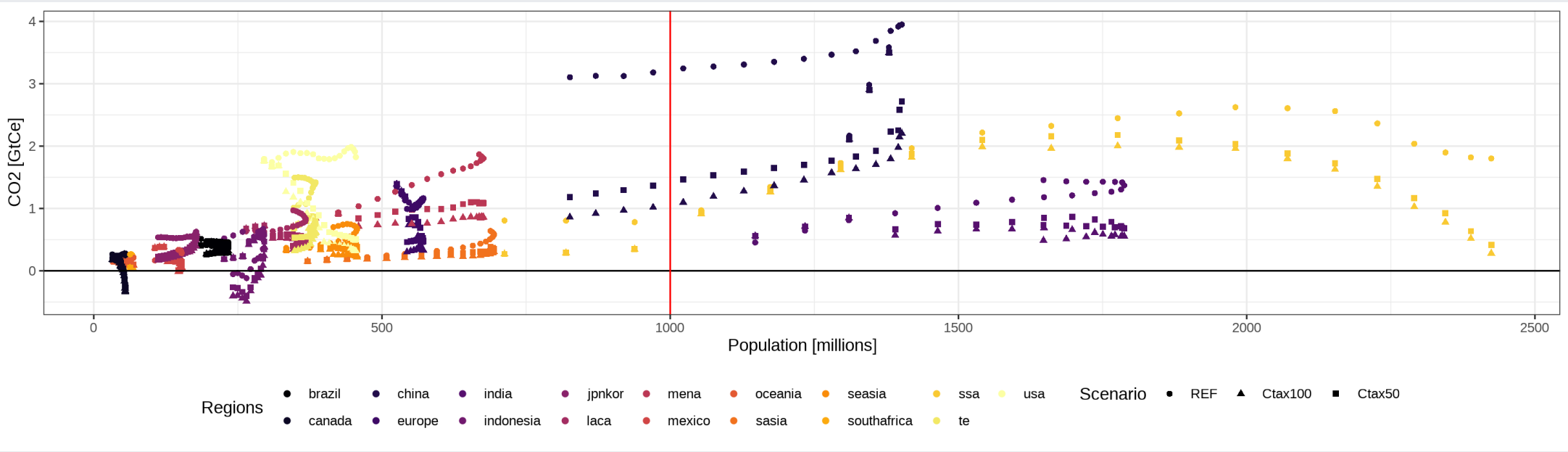
Change names of legend and add guide lines

```
ggplot(data=dat[t<2100 & e=='kghg'], aes(x=value.pop,y=value.ghg,color=n))+
 geom_point() + theme_bw() +
 scale_x_continuous(name="Population [millions]") +
 scale_y_continuous(name="CO2 [GtCe]")+
 scale_color_viridis(name="Regions",discrete = TRUE, option = "B")+ # choosing another option
 guides(col = guide_legend(ncol = 9))+ # divide in 9 columns
 theme(legend.position="bottom") + # put on top
 geom_hline(yintercept=0)+ # add a horizontal line
 geom_vline(xintercept=1000,color='red') # separate high population regions
```



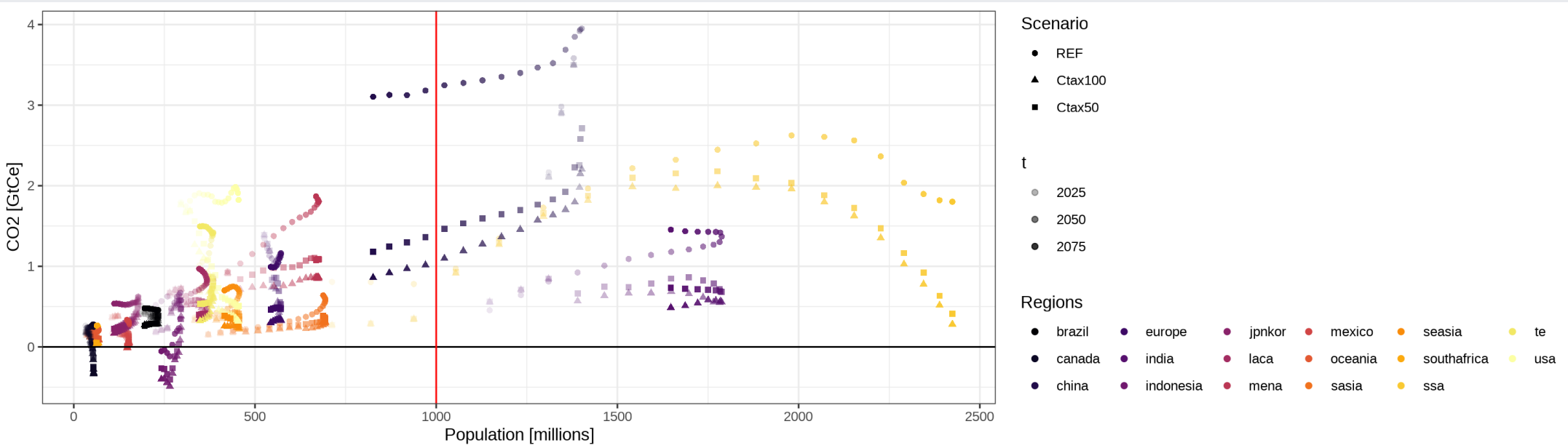
Scatter plots - Add one more dimention

```
 ggplot(data=dat[t<2100 & e=='kghg'], aes(x=value.pop,y=value.ghg,color=n,shape=Scenario))+ # add shape
  geom_point() + theme_bw() +
  scale_x_continuous(name="Population [millions]") +
  scale_y_continuous(name="CO2 [GtCe]")+
  scale_color_viridis(name="Regions",discrete = TRUE, option = "B")+ # choosing another option
guides(col = guide_legend(ncol = 9))+ # divide in 9 columns
  theme(legend.position="bottom")+ # put on top
  geom_hline(yintercept=0)+
  geom_vline(xintercept=1000,color='red')
```



Scatter plots - Add yet another dimention

```
ggplot(data=dat[t<2100 & e=='kghg'], aes(x=value.pop,y=value.ghg,color=n,shape=Scenario,alpha=t))+ # add transparency
 geom_point() + theme_bw() +
 scale_x_continuous(name="Population [millions]") +
 scale_y_continuous(name="CO2 [GtCe]")+
 scale_color_viridis(name="Regions",discrete = TRUE, option = "B")+
 guides(col = guide_legend(ncol = 6))+
 theme(legend.position="right")+ # put on to right
 geom_hline(yintercept=0)+
 geom_vline(xintercept=1000,color='red')
```

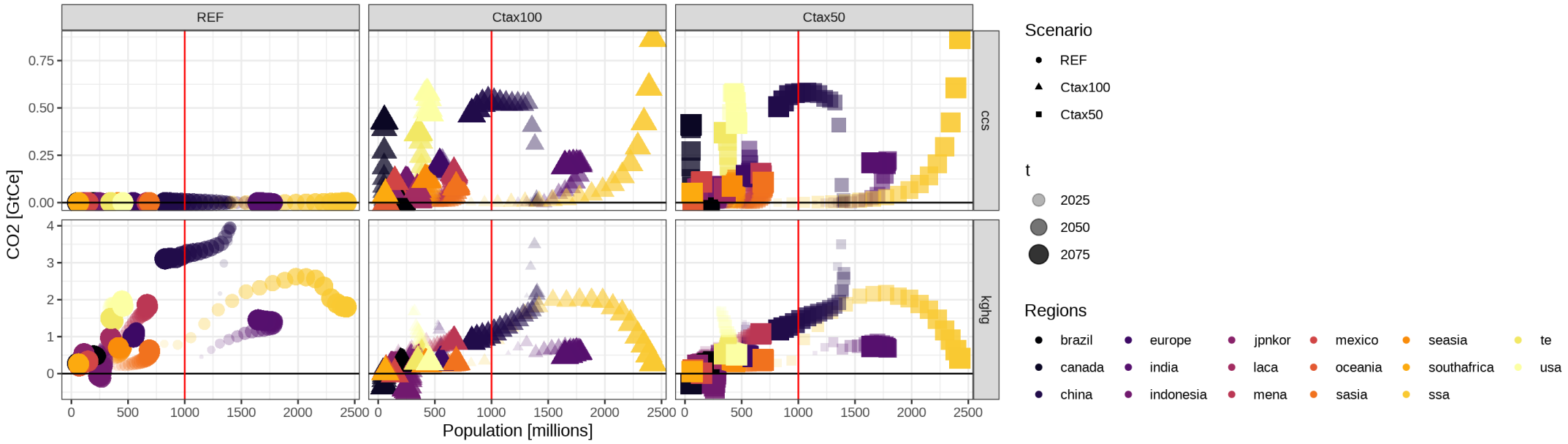


Scatter plots - and one more ... too many!

```
ggplot(data=dat[t<2100 ],  aes(x=value.pop,y=value.ghg,color=n,shape=Scenario,alpha=t,size=e))+ # add size with parameter 'e'
 geom_point() + theme_bw(base_size = 8) +
 scale_x_continuous(name="Population [millions]") +
 scale_y_continuous(name="CO2 [GtCe]")+
 scale_color_viridis(name="Regions",discrete = TRUE, option = "B")+
 guides(col = guide_legend(ncol = 6))+
 theme(legend.position="right")+
 geom_hline(yintercept=0)+
 geom_vline(xintercept=1000,color='red')
```

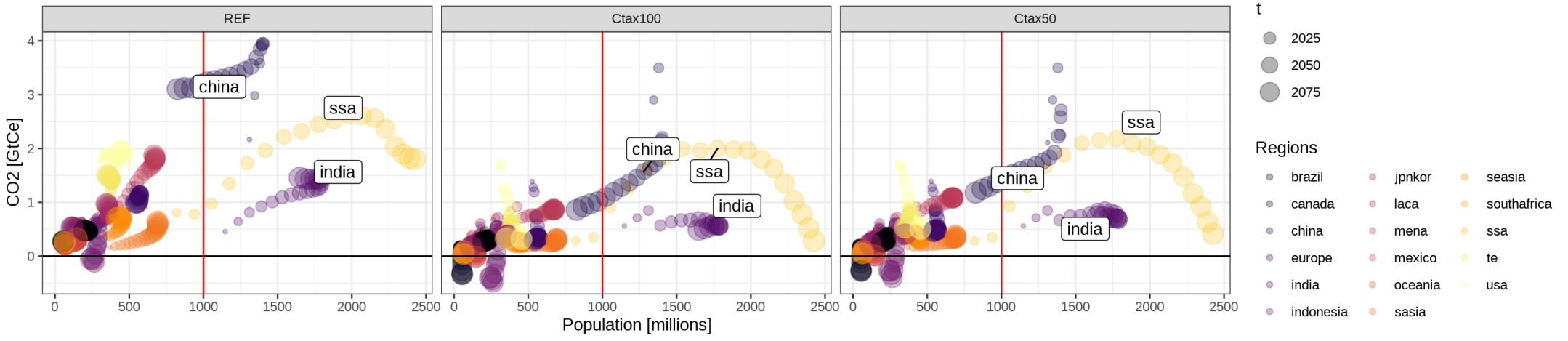
Scatter plots - Let's exagerate

```
ggplot(data=dat[t<2100 ],  aes(x=value.pop,y=value.ghg,color=n,shape=Scenario,alpha=t,size=t))+
 geom_point() + theme_bw() +
 scale_x_continuous(name="Population [millions]") +
 scale_y_continuous(name="CO2 [GtCe]")+
 scale_color_viridis(name="Regions",discrete = TRUE, option = "B")+
 guides(col = guide_legend(ncol = 6))+
 theme(legend.position="right")+
 geom_hline(yintercept=0)+
 geom_vline(xintercept=1000,color='red')+
 facet_grid(e~Scenario,scales='free')
```



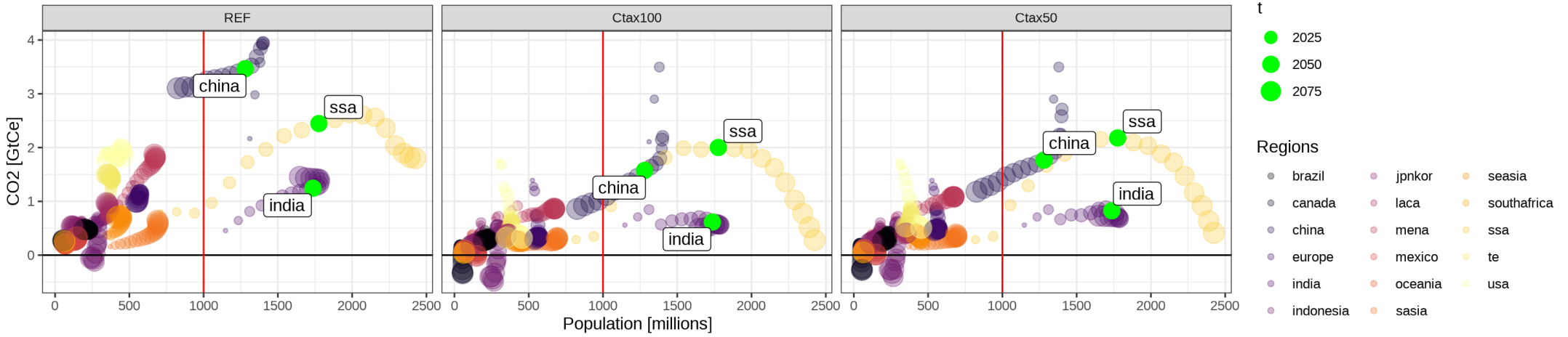
Scatter plots - help the reader

```
library(ggrepel)
   ggplot(data=dat[t<2100 & e=='kghg'], aes(x=value.pop,y=value.ghg,color=n))+
    geom_point(aes(size=t),alpha=0.3) + theme_bw() +
    scale_x_continuous(name="Population [millions]") +
    scale_y_continuous(name="CO2 [GtCe]")+
    scale_color_viridis(name="Regions",discrete = TRUE, option = "B")+
    guides(col = guide_legend(ncol = 3))+ # divide in 3 columns
    theme(legend.position="right")+
    geom_hline(yintercept=0)+
    geom_vline(xintercept=1000,color='red')+
    geom_label_repel(data=dat[t==2050 & value.pop>1000 & e=='kghg'],
                     aes(x=value.pop,y=value.ghg,label=n),color='black') + # draw attention to ...
    facet_grid(~Scenario,scales='free')
```



Scatter plots - Draw attention to ...

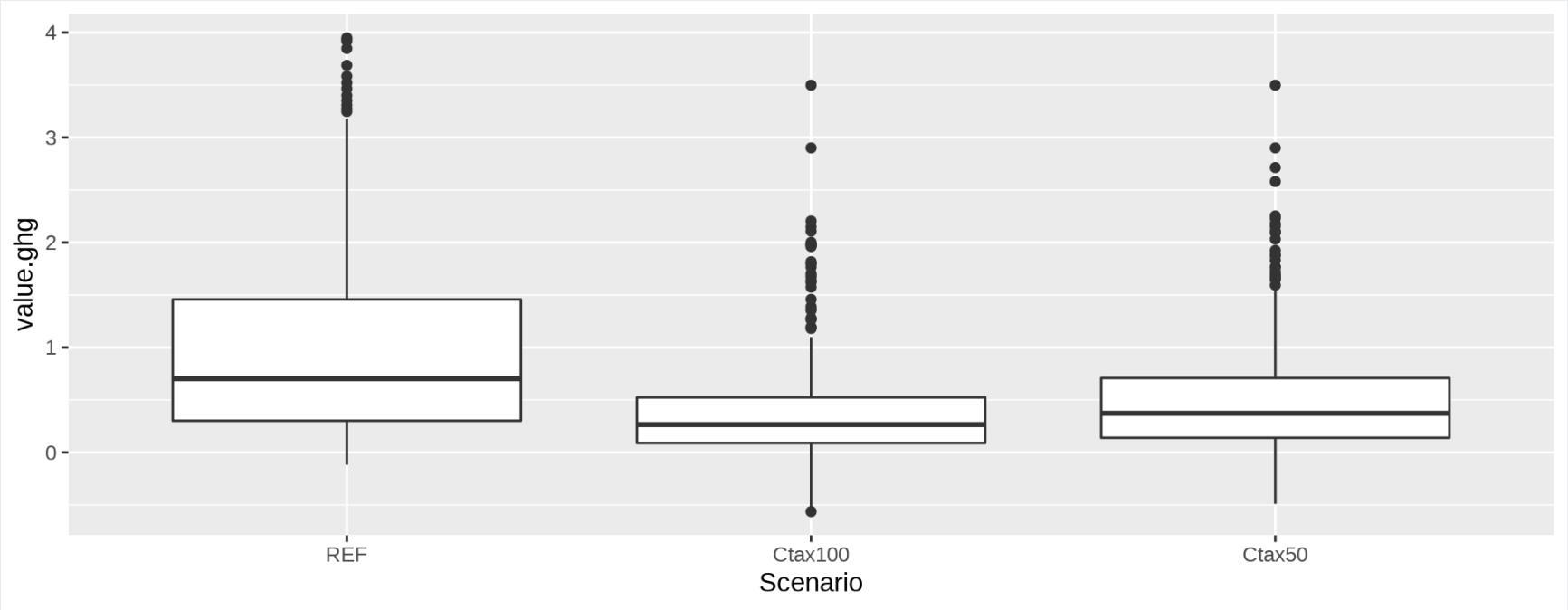
```
ggplot(data=dat[t<2100 & e=='kghg'], aes(x=value.pop,y=value.ghg,color=n))+
 geom_point(aes(size=t),alpha=0.3) + theme_bw() +
 scale_x_continuous(name="Population [millions]") +
 scale_y_continuous(name="CO2 [GtCe]")+
 scale_color_viridis(name="Regions",discrete = TRUE, option = "B")+
 guides(col = guide_legend(ncol = 3))+ # divide in 3 columns
 theme(legend.position="right")+
 geom_hline(yintercept=0)+
 geom_vline(xintercept=1000,color='red')+
 geom_point(data=dat[t==2050 & value.pop>1000 & e=='kghg'],
                  aes(x=value.pop,y=value.ghg,size=t),color='green')+#emphasize a few points
 geom_label_repel(data=dat[t==2050 & value.pop>1000 & e=='kghg'],
                  aes(x=value.pop,y=value.ghg,label=n),color='black') + #draw attention to ...
 facet_grid(~Scenario,scales='free')
```



Box plots - Plotting distributions

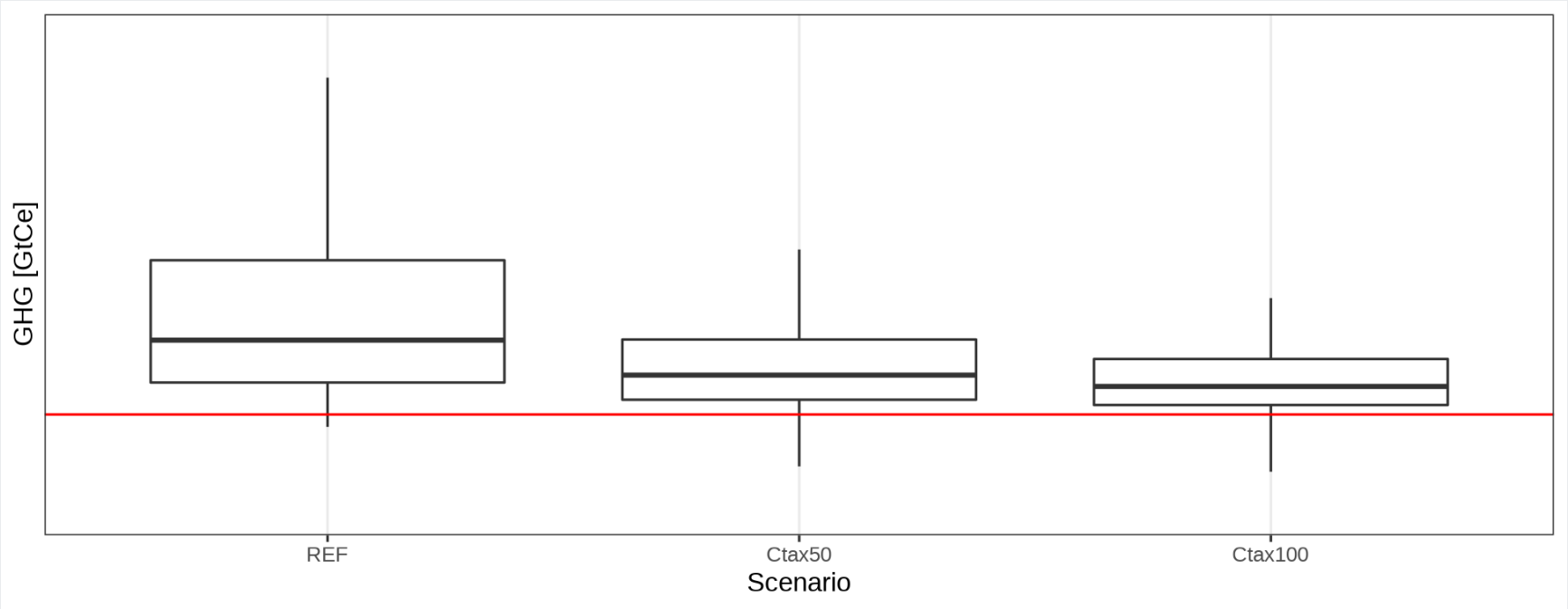
When mean or median are not enough

```
ggplot(data=dat[e=='kghg'], aes(x=Scenario,y=value.ghg))+
 geom_boxplot()
```



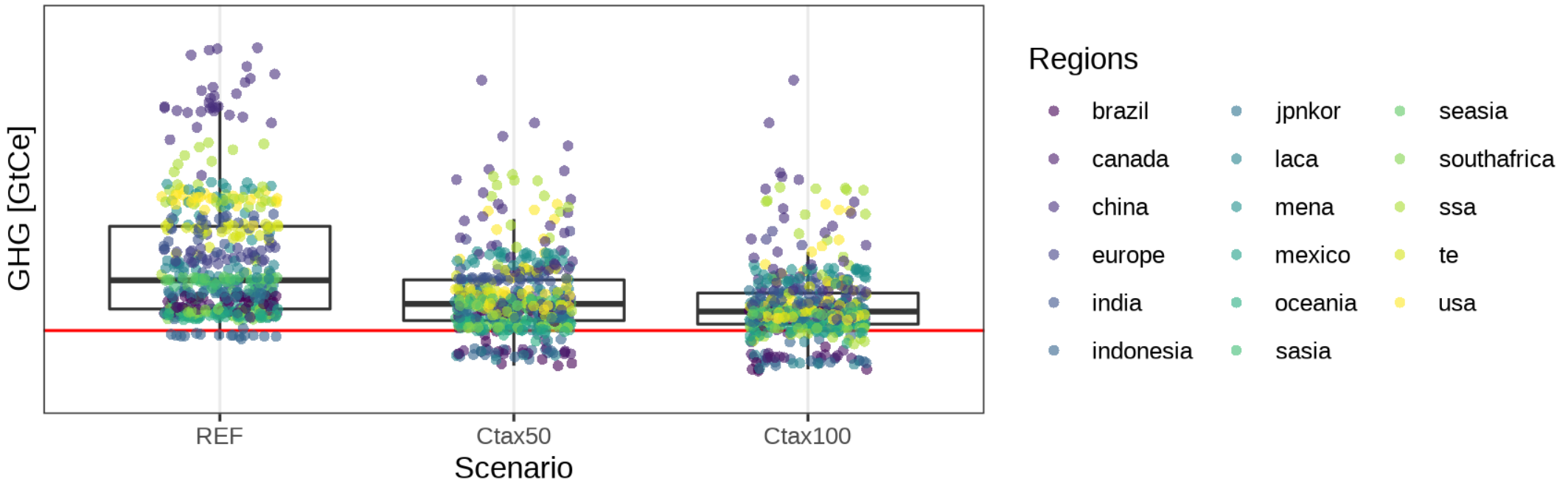
Box plots - typical retouch..

```
# order x by something that makes sense
dat$Scenario <- factor(dat$Scenario, levels = c("REF","Ctax50","Ctax100"))

ggplot(data=dat[e=='kghg'], aes(x=Scenario,y=value.ghg))+
 geom_boxplot(outlier.shape = NA) + theme_bw()+
 geom_hline(yintercept = 0,color="red")+
 scale_y_discrete(name="GHG [GtCe]")
```



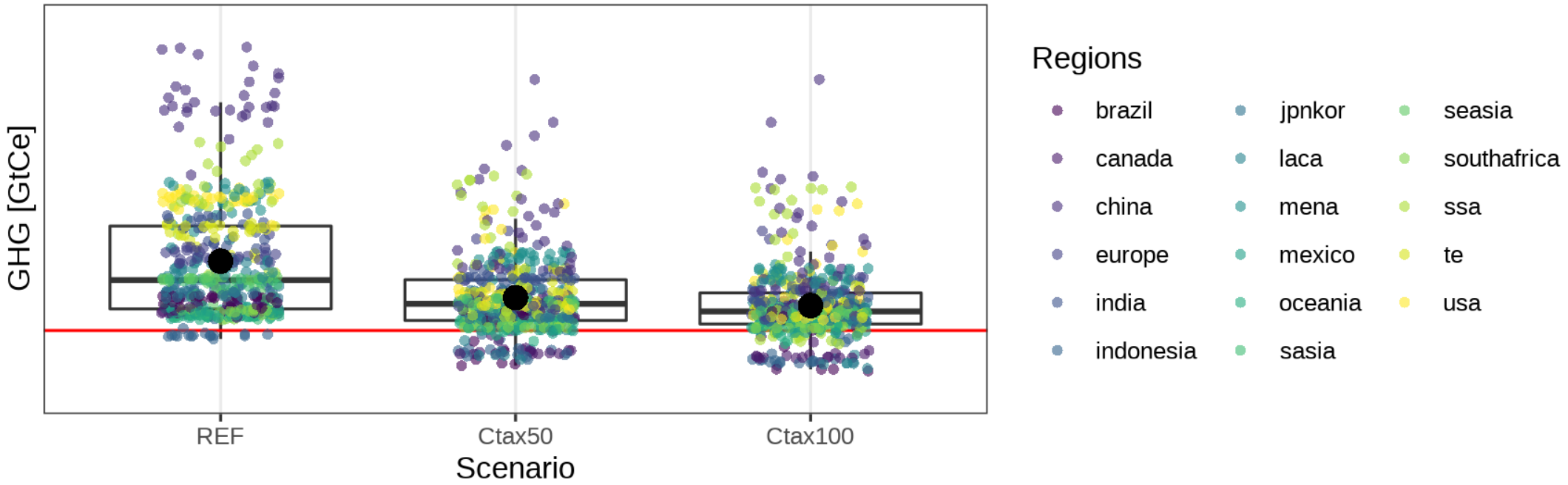
Box plots - add the underlying observations

```
ggplot(data=dat[e=='kghg'], aes(x=Scenario,y=value.ghg))+
 geom_boxplot(outlier.shape = NA) + theme_bw()+
 geom_hline(yintercept = 0,color="red")+
 scale_y_discrete(name="GHG [GtCe]")+
 geom_jitter(aes(color=n),shape=16, position=position_jitter(0.2),alpha=0.6)+ # add all points
 scale_color_viridis(name="Regions",discrete = TRUE, option = "D")+
 guides(col = guide_legend(ncol = 3))# color per region
```

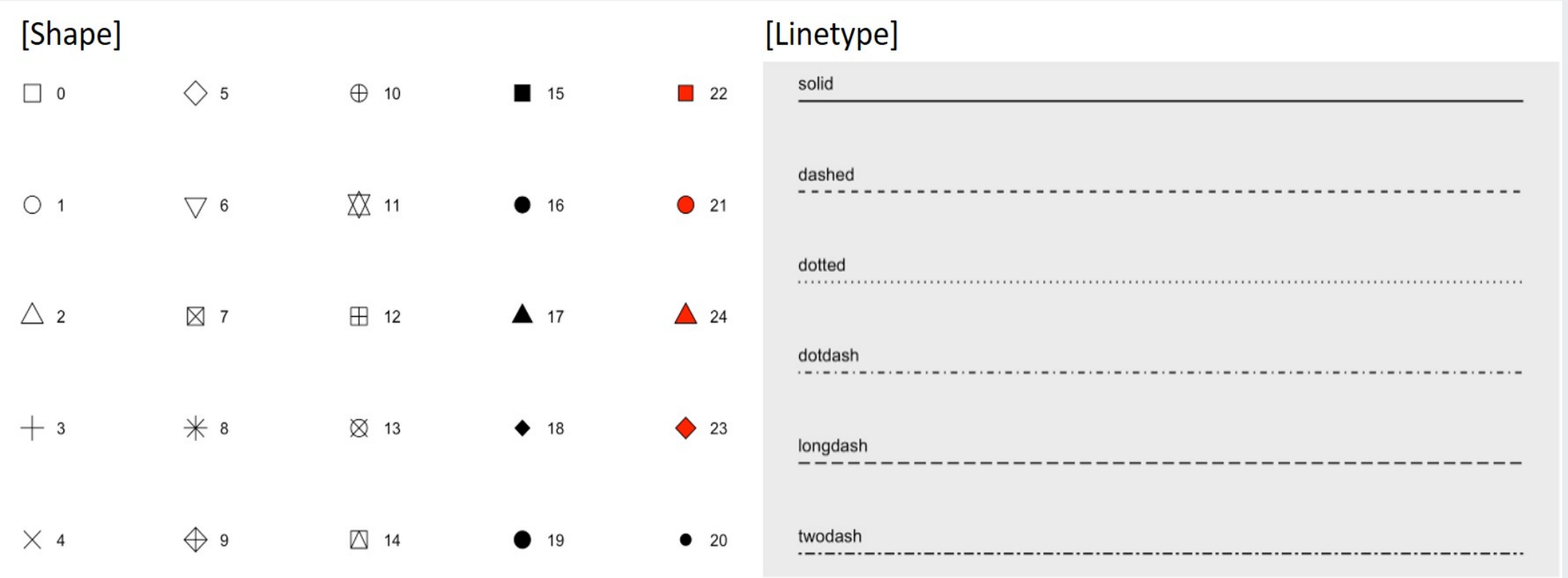


Box plots - add more infomation

```
ggplot(data=dat[e=='kghg'], aes(x=Scenario,y=value.ghg))+
 geom_boxplot(outlier.shape = NA) + theme_bw()+
 geom_hline(yintercept = 0,color="red")+
 scale_y_discrete(name="GHG [GtCe]")+
 geom_jitter(aes(color=n),shape=16, position=position_jitter(0.2),alpha=0.6)+
 scale_color_viridis(name="Regions",discrete = TRUE, option = "D")+
 guides(col = guide_legend(ncol = 3)) +
 stat_summary(data=dat[e=='kghg'], aes(x=Scenario,y=value.ghg),fun=mean, geom="point", shape=16, size=4)
```



Shapes and linetypes



Maps - Showing regional information

We need to prepare the data first

```
# import the WITCH model regional definition
wreg = fread('Material/mapwitch17.csv',header = TRUE)
# we will need a new library
library(countrycode)

 wreg$region = wreg$ISO
 # transforms ISO codes into country names
 wreg$region = countrycode(wreg$ISO, origin = 'iso3c', destination = 'country.name')
 # correcting some mismatches
 wreg[grep('Congo',wreg$region)]$region = c("Democratic Republic of the Congo", "Republic of Congo"  )
 wreg[region=='Bosnia & Herzegovina']$region = 'Bosnia and Herzegovina'
 wreg[region=='Myanmar (Burma)']$region = 'Myanmar'
 wreg[region=='Côte d'Ivoire']$region = 'Ivory Coast'
 wreg[region=='Czechia']$region = 'Czech Republic'
 wreg[ISO=='GBR']$region = 'UK'
 wreg[ISO=='USA']$region = 'USA'
```

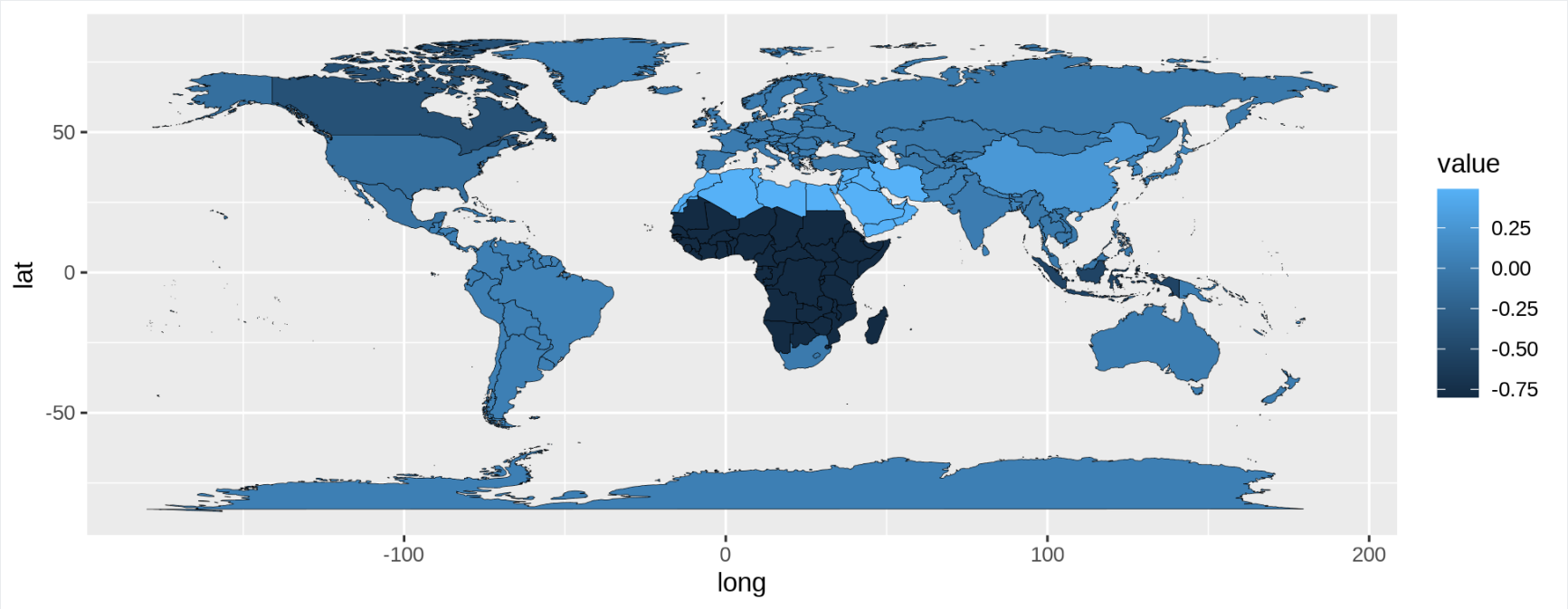
Maps - Showing regional information

```
# Retrieve the world data for the regions of WITCH
world.maps <- map_data("world")

# let's transform it into a data.table
world.maps  = setDT(world.maps )

# merge the WITCH regional definition with the world map
world.maps  = merge(world.maps,wreg,by='region',allow.cartesian=TRUE)

# merge with our regional GHG data.table
# let's choose an year, a pollutant
mGHG=merge(world.maps,GHG[t==2100 & e=='co2' ],by=c('n'),allow.cartesian=TRUE)
```

Ready to plot the map now!

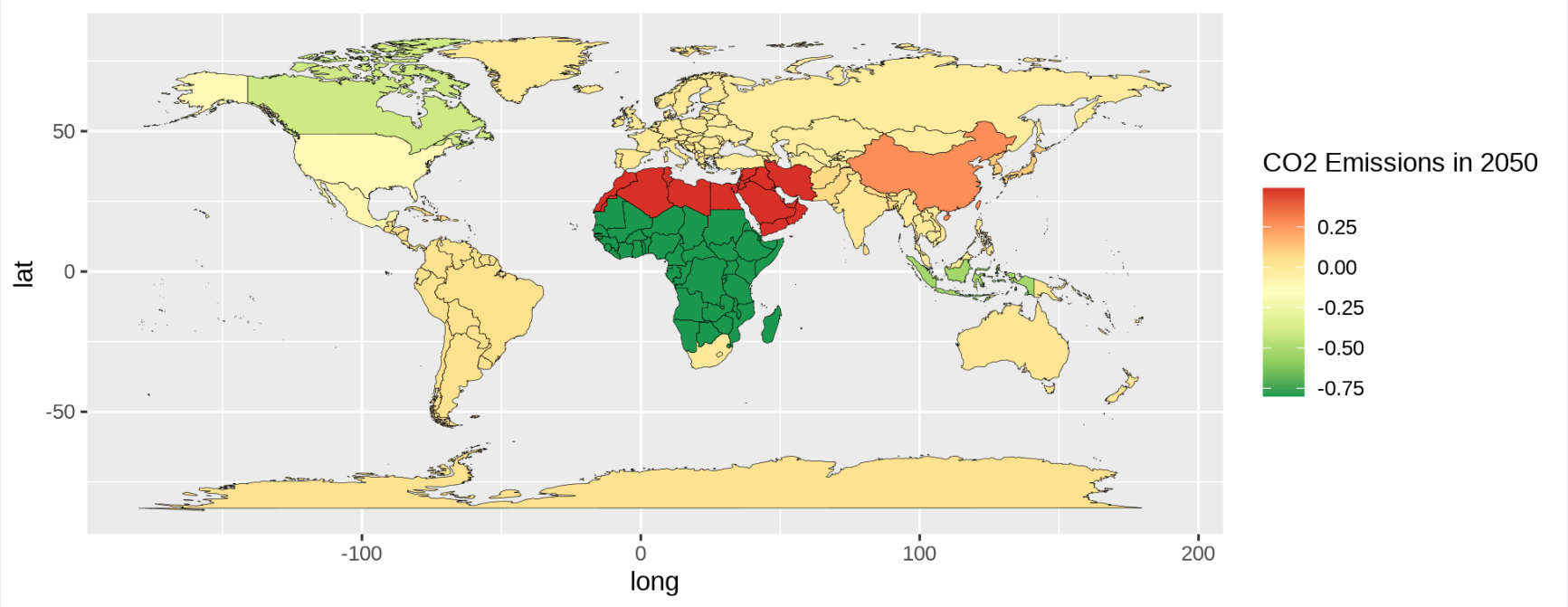
Maps - Showing regional information

```
ggplot(mGHG[ Scenario=='Ctax100',], aes(x = long, y = lat)) +
  geom_polygon(aes( group = group, fill = value),color='black',size=.1)
```



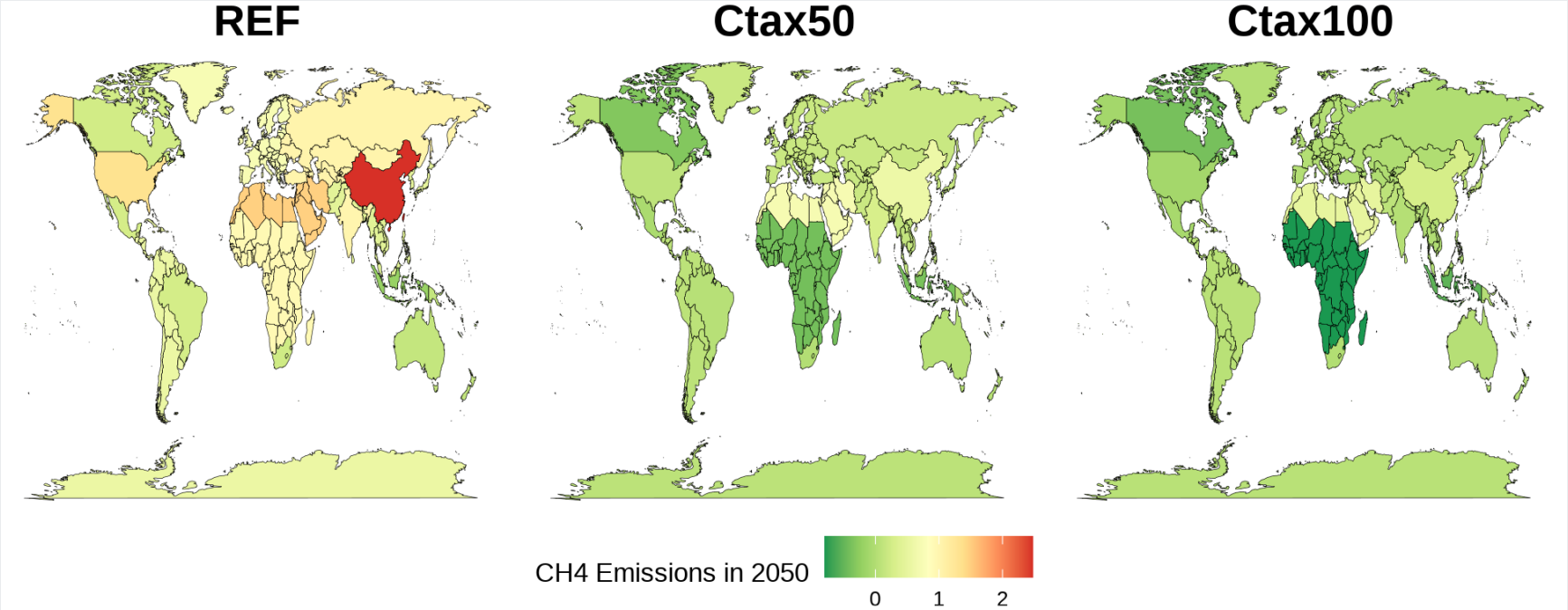
Maps - color pallets are important

```
ggplot(mGHG[ Scenario=='Ctax100',], aes(x = long, y = lat)) +
  geom_polygon(aes( group = group, fill = value),color='black',size=.1)+
  scale_fill_distiller(name = "CO2 Emissions in 2050",palette ="RdYlGn",direction=-1) #revert color
```



Maps - Apply the tricks you already know

```
mGHG$Scenario <- factor(mGHG$Scenario, levels = c("REF","Ctax50","Ctax100"))
  ggplot(mGHG, aes(x = long, y = lat)) +
    geom_polygon(aes( group = group, fill = value),color='black',size=.1)+
    theme_void()+ # clean the background
    scale_fill_distiller(name = "CH4 Emissions in 2050",palette ="RdYlGn",direction=-1)+ # revert color
     theme(legend.position = "bottom", strip.text.x = element_text(size=18, face="bold"))+
    facet_grid(~Scenario)
```

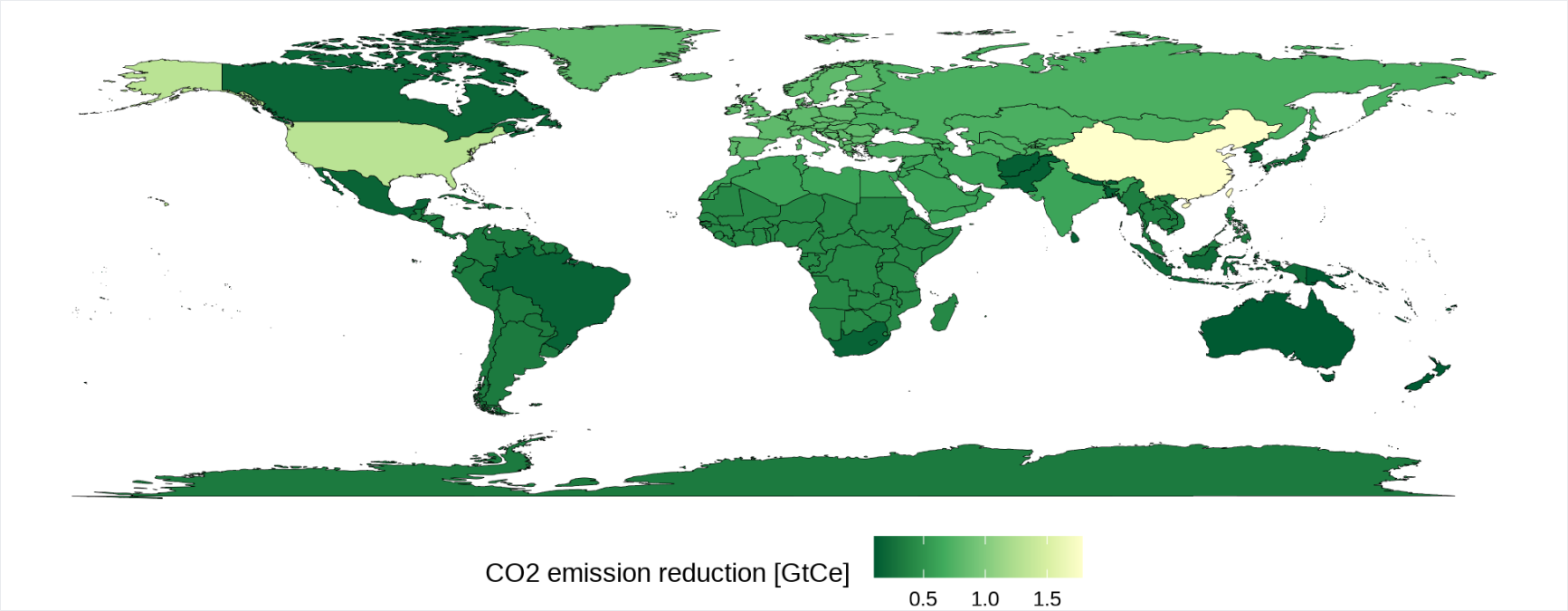


Transforming variables

```
# let's transform GHG by having the scenarios as columns while keeping the rest of the structure
dGHG = dcast(GHG[e=='co2',], ... ~  Scenario , value.var='value' )

# Let's create a new variable/column
dGHG$dif_wrtREF =  dGHG$REF - dGHG$Ctax100

# merge  our regional dGHG data.table to the world polygons as before
mpGHG=merge(world.maps,dGHG[t==2050 & e=='co2' ],by=c('n'),allow.cartesian=TRUE)
```

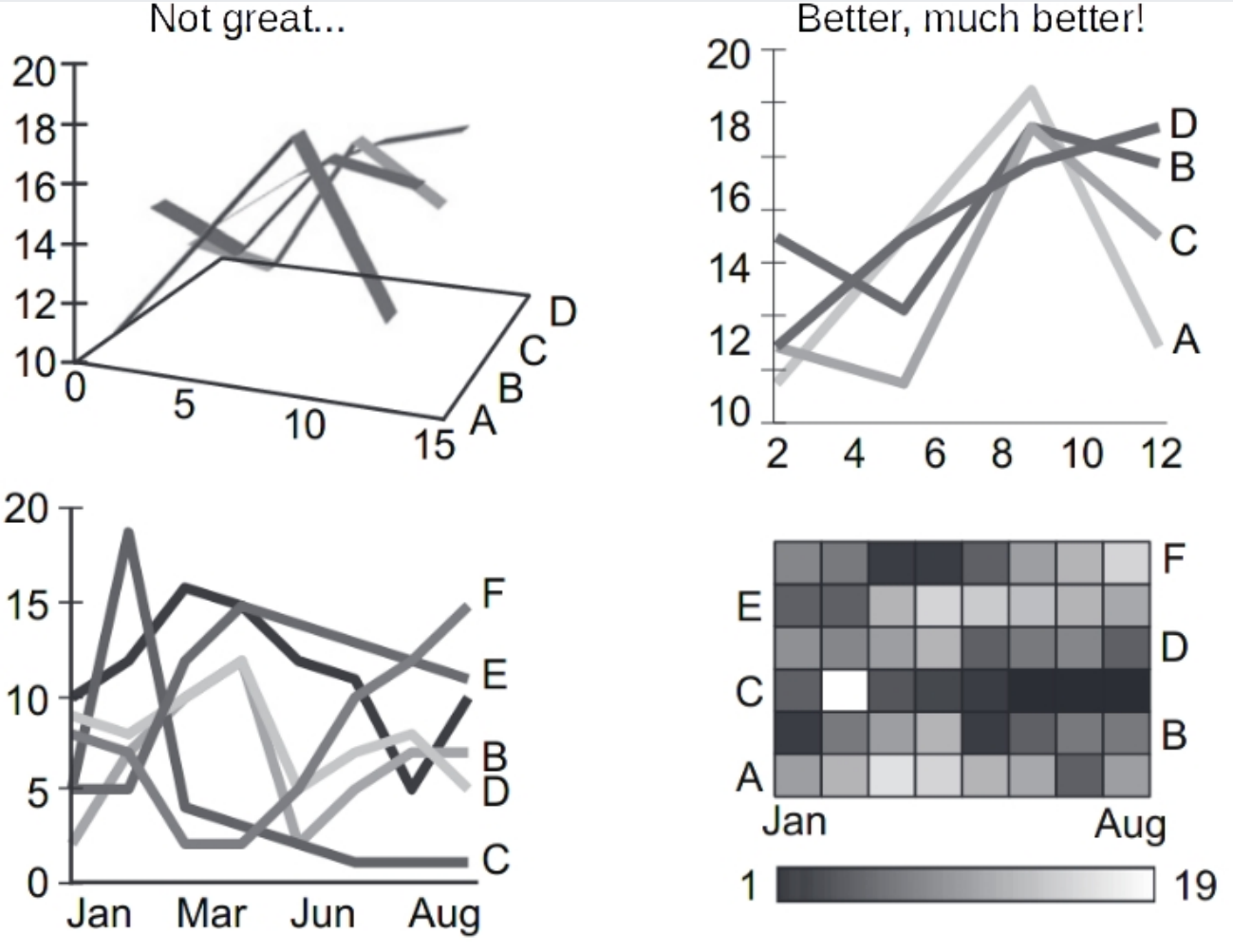
Transforming variables

```
ggplot(mpGHG, aes(x = long, y = lat)) +
 geom_polygon(aes( group = group, fill = dif_wrtREF),color='black',size=.1)+
 theme_void()+ # clean the background
 scale_fill_distiller(name = "CO2 emission reduction [GtCe] ",palette ="YlGn")+ #revert color
 theme(legend.position = "bottom", strip.text.x = element_text(size=18, face="bold"))
```



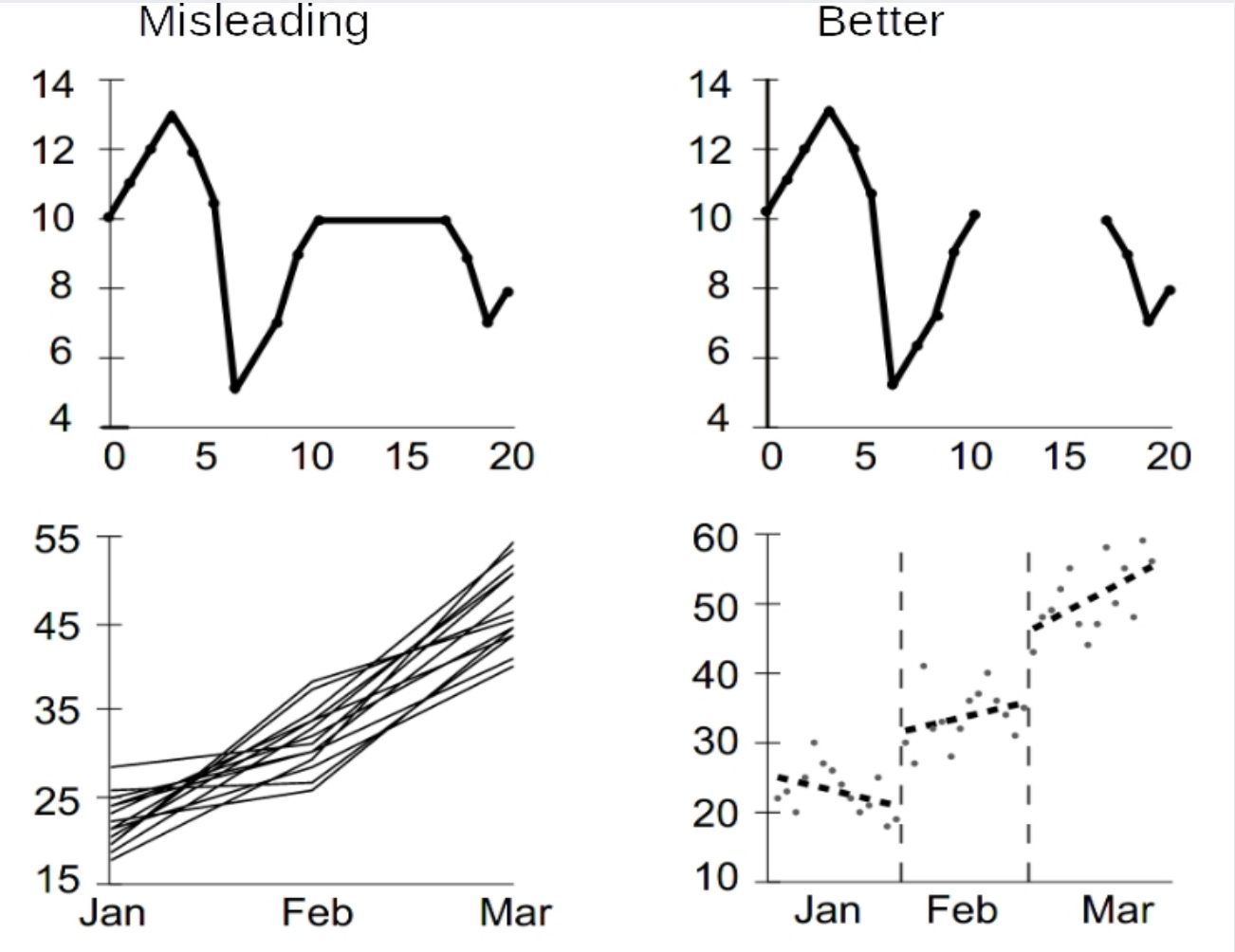
Tips for good visualization

Tips for good visualization



source: Kelleher et al. 2011

Tips for good visualization



source: Kelleher et al. 2011

Further Readings

GAMS

- GAMS documentation: https://www.gams.com/latest/docs

R

- Data Visualization in R: https://wilkelab.org/SDS375

ggplot2

- ggplot2 book https://ggplot2-book.org/
- ggplot2 reference documentation https://ggplot2.tidyverse.org/reference/index.html