GAMS-R Vizualization Lecture

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Presentation

Laurent Drouet

- Researcher at RFF-CMCC EIEE. WITCH model developer.
- Several **R** packages, in particular, `gdxtools`.
- GAMS extension for the editor `Visual Code Studio`.

Lara Aleluia Reis

- She developed these slides.
- Environmental engineer
- Air pollution modeling (**R**)
- WITCH model developer at RFF-CMCC EIEE (**GAMS**+**R**).
- More than 10 years of **R** experience.

This lecture

In this lecture, you will learn how to use **R** with GAMS and for visualization.

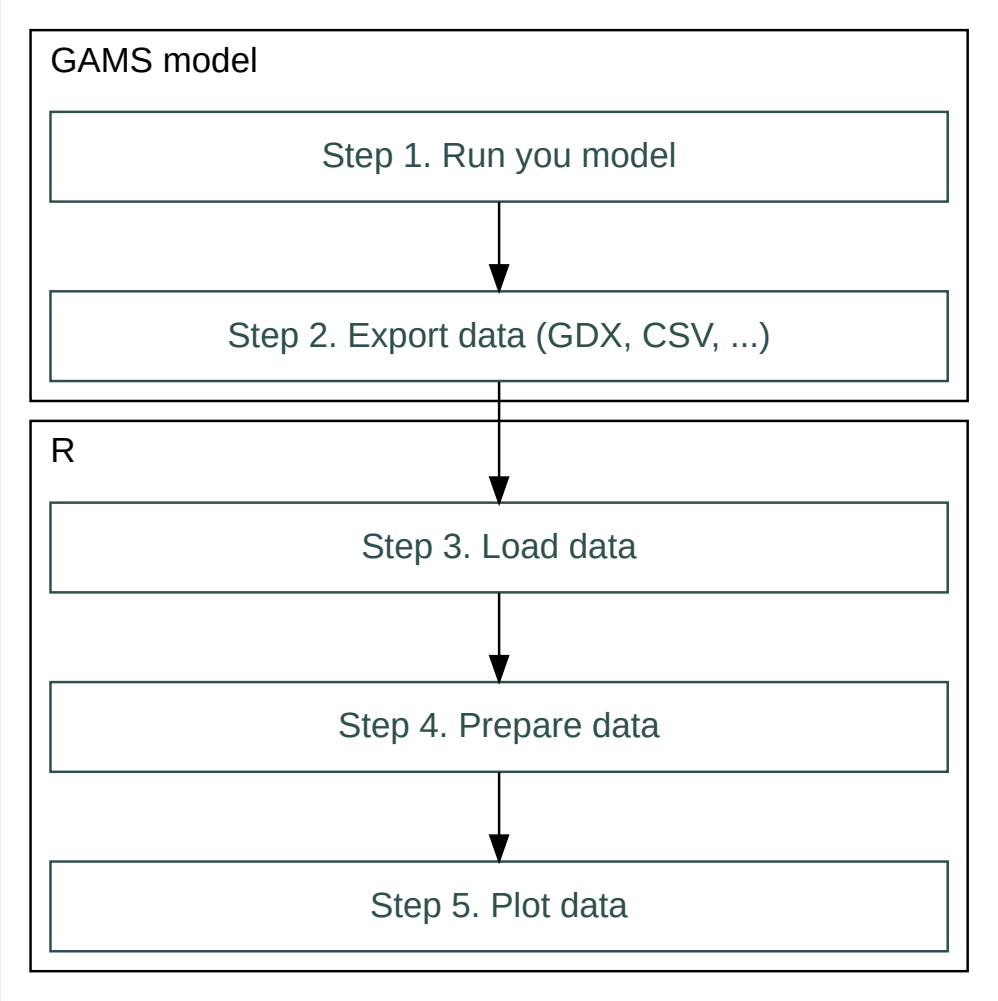
GAMS

- Read GAMS output through the GDX format.

Visualization

- Plot the model outputs
- Check the behavior of the model
- Understand the model results

Workflow


GAMS model
Step 1. Run you model
Step 2. Export data (GDX, CSV, ...)
R
Step 3. Load data
Step 4. Prepare data
Step 5. Plot data

Outline

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

How to Start: Requirements

> R, RStudio and R packages are required for the rest of the lecture

1. Install R: https://cloud.r-project.org
2. Install Rstudio IDE: https://www.rstudio.com/products/rstudio/download
3. Install Rtools (for `gdxtools`): https://cran.r-project.org/bin/windows/Rtools/rtools40.html

We need to install the following R packages for the lecture:

```
'tidyverse'
'gdxtools' # Installation instructions → https://github.com/lolow/gdxtools
```

Open RStudio and paste the following command in the console:

```
install.packages('tidyverse')
```

The GAMS data exchange GDX files

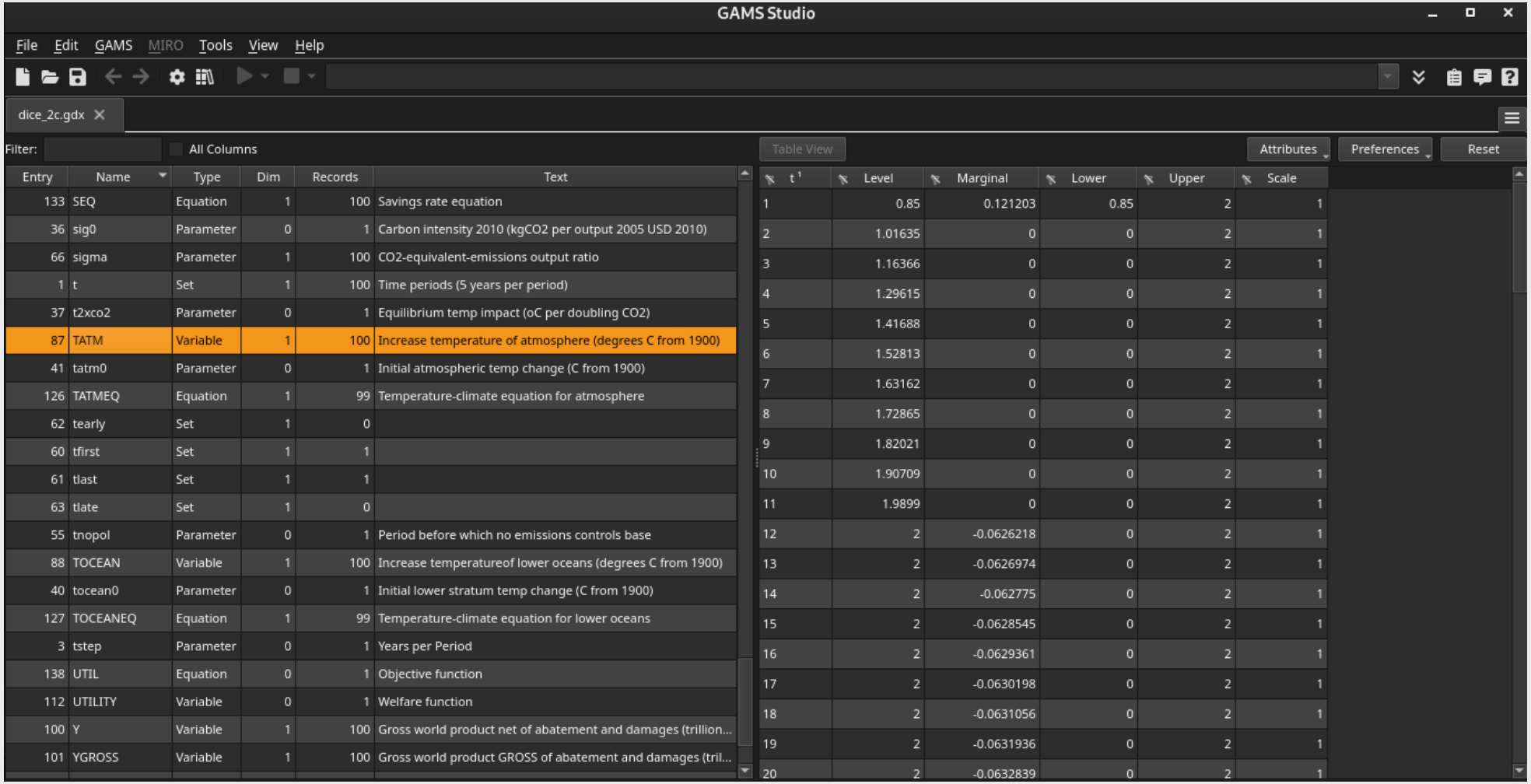
The GAMS data exchange files

The GAMS data exchange format (in short GDX) is a proprietary file format to store the various elements of a GAMS model.

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

Many information is stored in the GDX file. For example, for the variables, the GDX contain the values (`level`), the bounds (`lower`,`upper`), the marginal value (`marginal`) and the scaling factors (`scale`).

Browsing a GDX in GAMS studio



Entry	Name	Type	Dim	Records	Text
133	SEQ	Equation	1	100	Savings rate equation
36	sig0	Parameter	0	1	Carbon intensity 2010 (kgCO2 per output 2005 USD 2010)
66	sigma	Parameter	1	100	CO2-equivalent-emissions output ratio
1	t	Set	1	100	Time periods (5 years per period)
37	t2xco2	Parameter	0	1	Equilibrium temp impact (oC per doubling CO2)
87	TATM	Variable	1	100	Increase temperature of atmosphere (degrees C from 1900)
41	tatm0	Parameter	0	1	Initial atmospheric temp change (C from 1900)
126	TATMEQ	Equation	1	99	Temperature-climate equation for atmosphere
62	tearly	Set	1	0	
60	tfirst	Set	1	1	
61	tlast	Set	1	1	
63	tlate	Set	1	0	
55	tnopol	Parameter	0	1	Period before which no emissions controls base
88	TOCEAN	Variable	1	100	Increase temperatureof lower oceans (degrees C from 1900)
40	tocean0	Parameter	0	1	Initial lower stratum temp change (C from 1900)
127	TOCEANEQ	Equation	1	99	Temperature-climate equation for lower oceans
3	tstep	Parameter	0	1	Years per Period
138	UTIL	Equation	0	1	Objective function
112	UTILITY	Variable	0	1	Welfare function
100	Y	Variable	1	100	Gross world product net of abatement and damages (trillion...
101	YGROSS	Variable	1	100	Gross world product GROSS of abatement and damages (tril...

t [1]	Level	Marginal	Lower	Upper	Scale
1	0.85	0.121203	0.85	2	1
2	1.01635	0	0	2	1
3	1.16366	0	0	2	1
4	1.29615	0	0	2	1
5	1.41688	0	0	2	1
6	1.52813	0	0	2	1
7	1.63162	0	0	2	1
8	1.72865	0	0	2	1
9	1.82021	0	0	2	1
10	1.90709	0	0	2	1
11	1.9899	0	0	2	1
12	2	-0.0626218	0	2	1
13	2	-0.0626974	0	2	1
14	2	-0.062775	0	2	1
15	2	-0.0628545	0	2	1
16	2	-0.0629361	0	2	1
17	2	-0.0630198	0	2	1
18	2	-0.0631056	0	2	1
19	2	-0.0631936	0	2	1
20	2	-0.0632839	0	2	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:

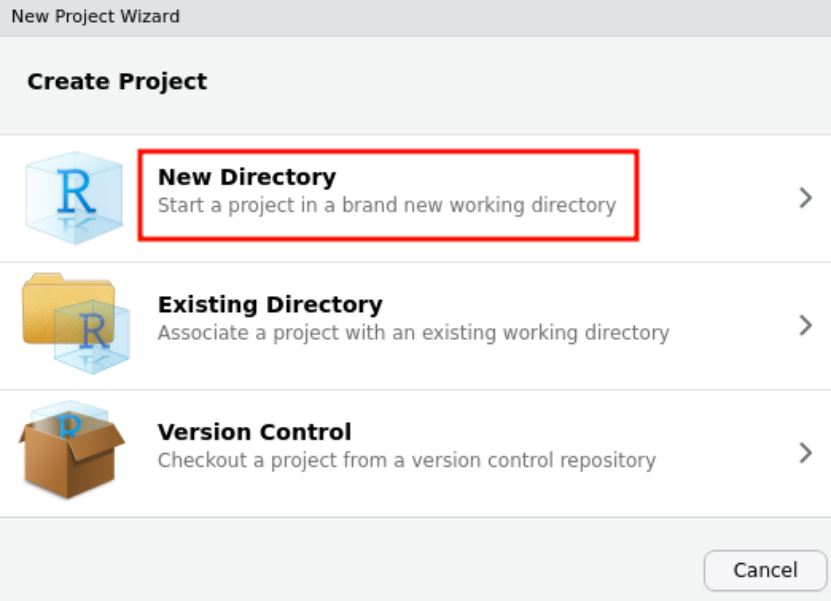
```
execute_unload "results.gdx", VAR1, VAR2, parameter1;
```

> Some models, like WITCH, already produce automatically a GDX of their results.

R Basics

Create an R project in RStudio

First, create a new R project (`File > New Project ...`) then `New Directory`

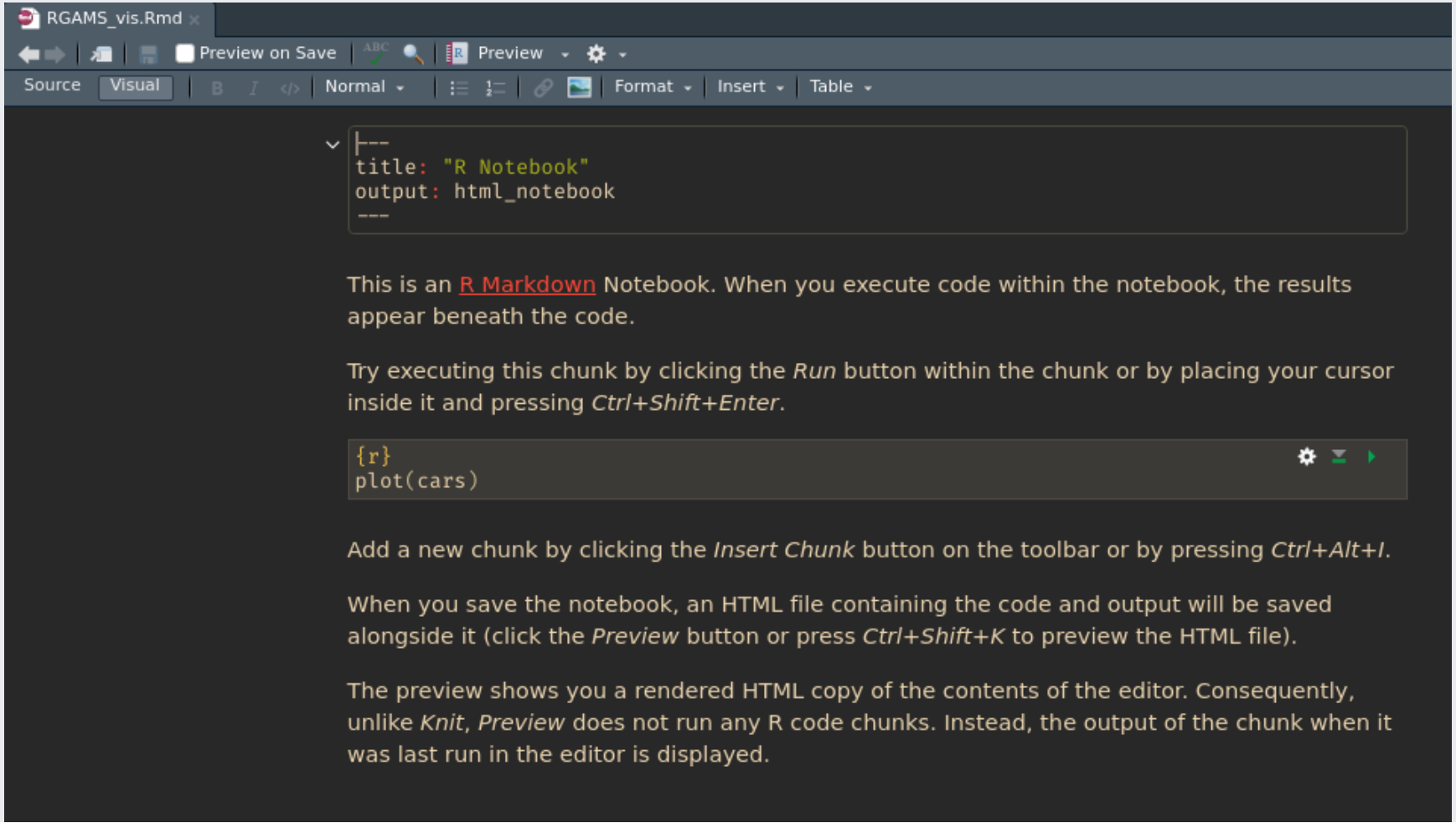


Choose your subdirectory and enter the name of the R project (for example, **`RGAMS_viz`**).

This will create a directory with the project name. Copy the `Material` folder inside.

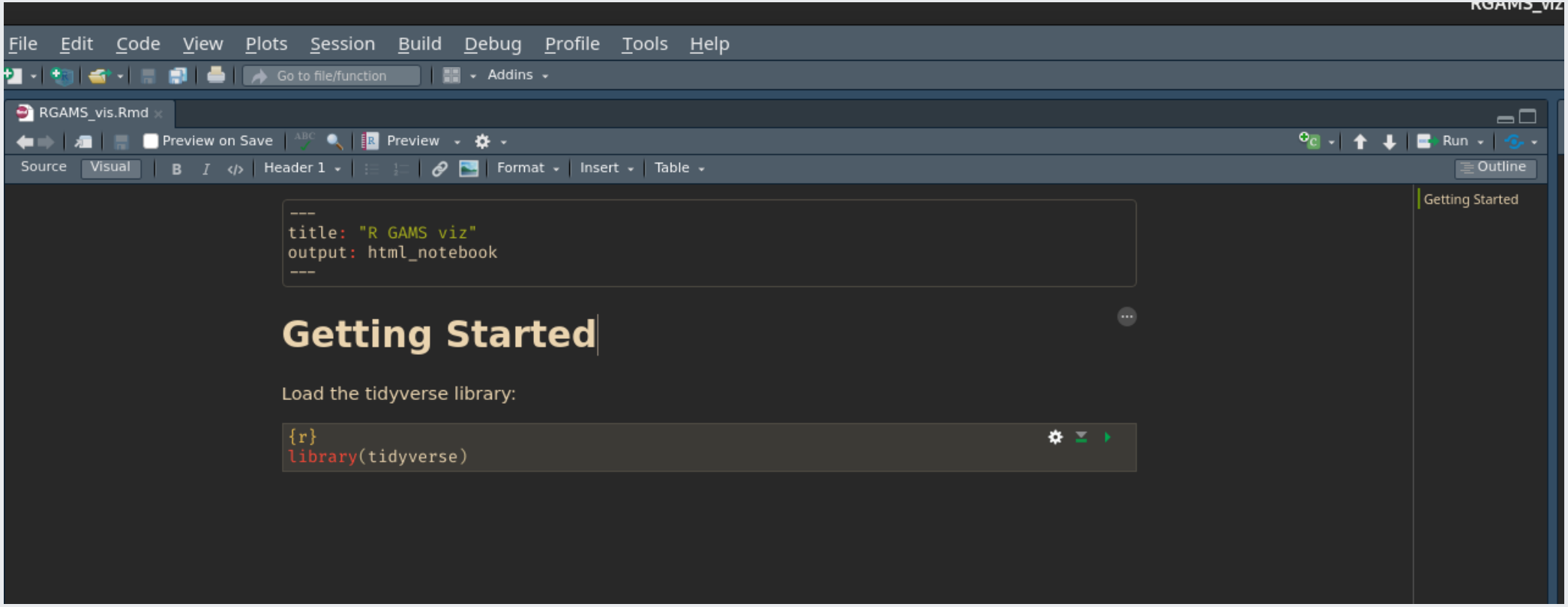
Create an R notebook

Create a new R Markdown file (`File > New File > R Markdown ...`). Click on `Visual` to access the visual editor.



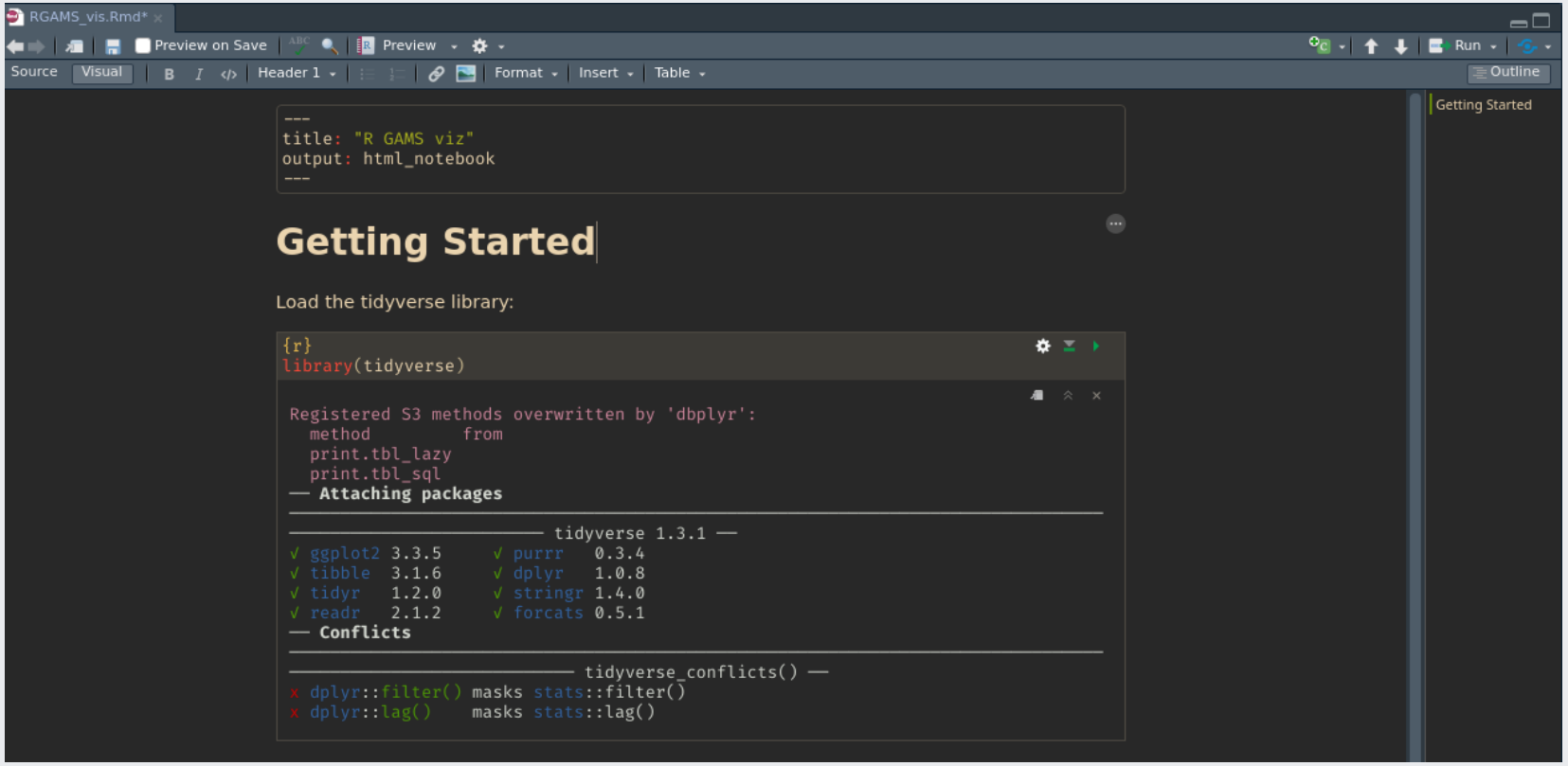
Update the notebook

Update the title, Remove the text and add a **R** chunk loading the `tidyverse` library.



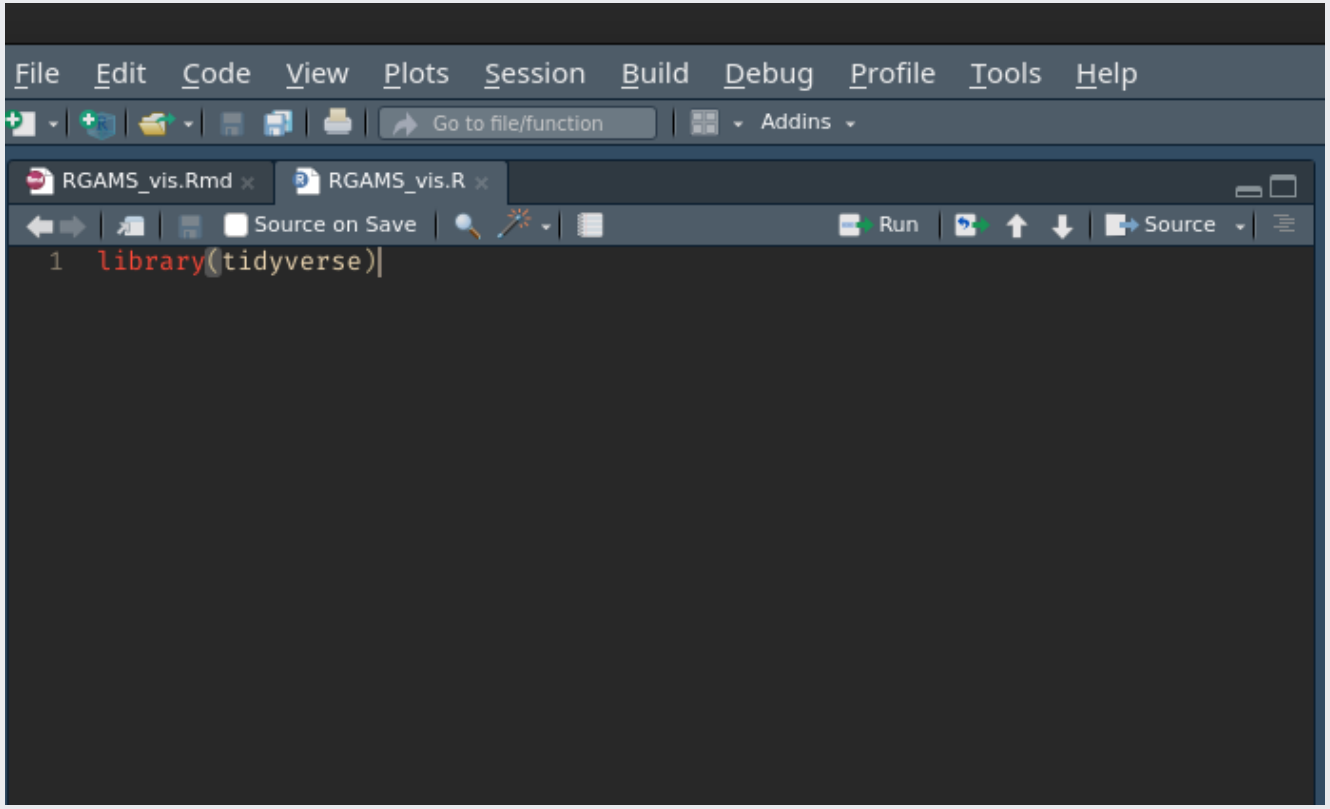
Execute the R chunk

Click on the *green* arrow on the top of the chunk.



R script

This is equivalent to create a proper Rscript (executable with `Source`):



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

In the console:

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

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

On windows, you need to install `Rtools` to be able to install the package. See the procedure at https://cran.r-project.org/bin/windows/Rtools

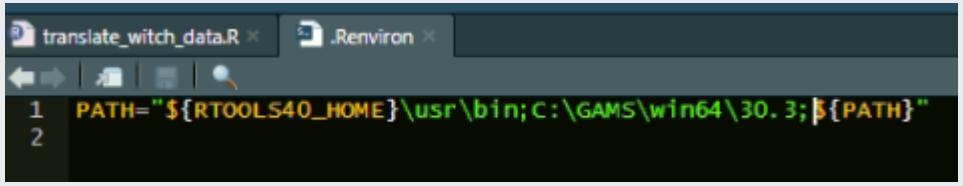
Usage

Load the package with

```
library(gdxtools)
```

`gdxtools` will try to find your `GAMS` installation. If it does not find it, choose one of the following solution:

- Tell windows about your GAMS path: https://helpdeskgeek.com/windows-10/add-windows-path-environment-variable
- Tell R about your GAMS path by adding it in your `.Renviron` file with `usethis::edit_r_environ()`



- Tell directly `gdxtools`:

```
igdx('C:\\GAMS\\win64\\38.1')
```

Usage

Connexion to a GDX file

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

```
mygdx ← gdx('Material/results_ssp2_bau.gdx')
```

`mygdx` can provide information on the GDX content.

```
mygdx
```

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

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

Usage

List of variables

```
mygdx$variables$name
```

```
##  [1] "UTILITY"           "PROB"              "I"                 "K"
##  [5] "Q"                 "BAU_Q"             "COST_Y"            "COST_EN"
##  [9] "COST_FUEL"         "FPRICE"            "I_EN"              "K_EN"
## [13] "MCOST_FUEL"        "MCOST_INV"         "QEL_OUT"           "QNEL_OUT"
## [17] "Q_EN"              "Q_FUEL"            "Q_IN"              "BAU_Q_EMI"
## [21] "COST_EMI"          "CPRICE"            "Q_EMI"             "I_RD"
## [25] "K_RD"              "SPILL"             "Q_EL_FLEX"         "K_EN_GRID"
## [29] "I_EN_GRID"         "CUM_Q_CCS"         "MCOST_EMI"         "Q_CCS"
## [33] "I_EN_WINDOFF"      "I_EN_WINDON"       "K_EN_WINDOFF"      "K_EN_WINDON"
## [37] "MCOST_INV_WINDOFF" "Q_EN_WINDOFF"      "Q_EN_WINDON"       "I_EN_PV"
## [41] "I_EN_CSP"          "K_EN_PV"           "K_EN_CSP"          "Q_EN_PV"
## [45] "Q_EN_CSP"          "ADDOILCAP"         "COST_OIL"          "CUM_OIL"
## [49] "I_OIL"             "I_OUT"             "OILCAP"            "OILPROD"
## [53] "Q_EMI_OUT"         "Q_OUT"             "RF"                "TEMP"
## [57] "TRF"               "W_EMI"             "WCUM_EMI"          "OMEGA"
## [61] "ELMOTOR_COST"
```

Usage

List of parameters

```
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"
##  [35] "l"                             "mer2ppp"
##  [37] "m_eqq_y"                       "ppp2mer"
##  [39] "q0"                            "rho"
##  [41] "tfpn"                          "tfpy"
##  [43] "ykali"                         "gdppc_kali"
##  [45] "cexs"                          "csi"
##  [47] "csi0"                          "cum_prodpp"
```

Usage

List of sets

```
mygdx$sets$name[1:60]
```

```
##  [1] "all_feasible"   "all_optimal"    "irep"           "iterrep"
##  [5] "tcheck"         "ierr"           "siter"          "conf"
##  [9] "t"              "tfix"           "tfirst"         "tlast"
## [13] "pre"            "n"              "oecd"           "non_oecd"
## [17] "clt"            "map_clt_n"      "negishi_coop"   "g"
## [21] "iq"             "extract"        "fuel"           "f"
## [25] "s"              "f_mkt"          "ices_el"        "j"
## [29] "j_to_scale"     "jel"            "jel_own_mu"     "jel_ren"
## [33] "jfed"           "jinv"           "jinv_own_k"     "jinv_to_scale"
## [37] "jmcost_inv"     "jnel"           "jnel_ren"       "jold"
## [41] "jpenalty"       "jreal"          "jreal_to_scale" "map_ices_el"
## [45] "map_j"          "cce"            "e"              "ghg"
## [49] "sink"           "c_mkt"          "map_e"          "jrd"
## [53] "jrd_lbd"        "leadrd"         "rd"             "rd_cooperation"
## [57] "rd_tgap"        "run"            "to_run"         "internal"
```

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`:

```
mygdx["wemi"] ▷ as_tibble() # use ▷ if R > 4.1 otherwise %>%
```

```
## # A tibble: 437 × 3
##    e     t     value
##    <chr> <chr> <dbl>
##  1 co2   1      8.56
##  2 co2   2      9.31
##  3 co2   3     10.1
##  4 co2   4     10.7
##  5 co2   5     11.4
##  6 co2   6     12.1
##  7 co2   7     12.5
##  8 co2   8     12.8
##  9 co2   9     12.7
## 10 co2   10    12.8
## # ℹ 427 more rows
```

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"] ▷ as_tibble()
```

```
## # A tibble: 16,830 × 4
##    e     t     n         value
##    <chr> <chr> <chr>     <dbl>
##  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
##  6 nip   1     indonesia     0
##  7 nip   1     jpnkor        0
##  8 nip   1     laca          0
##  9 nip   1     mena          0
## 10 nip   1     mexico        0
## # ℹ 16,820 more rows
```

Usage

To load the variable's upper bound:

```
mygdx["Q_EMI",field = "up"] ▷ as_tibble()
```

```
## # A tibble: 16,830 × 4
##    e     t     n         value
##    <chr> <chr> <chr>     <dbl>
##  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
##  6 nip   1     indonesia     0
##  7 nip   1     jpnkor        0
##  8 nip   1     laca          0
##  9 nip   1     mena          0
## 10 nip   1     mexico        0
## # ℹ 16,820 more rows
```

Usage

To load many gdx at once 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 ▷ as_tibble()
```

```
## # A tibble: 33,711 × 5
##    e     t     n         value gdx
##    <chr> <chr> <chr>     <dbl> <chr>
##  1 nip   1     brazil        0 Material/results_ssp2_bau.gdx
##  2 nip   1     canada        0 Material/results_ssp2_bau.gdx
##  3 nip   1     china         0 Material/results_ssp2_bau.gdx
##  4 nip   1     europe        0 Material/results_ssp2_bau.gdx
##  5 nip   1     india         0 Material/results_ssp2_bau.gdx
##  6 nip   1     indonesia     0 Material/results_ssp2_bau.gdx
##  7 nip   1     jpnkor        0 Material/results_ssp2_bau.gdx
##  8 nip   1     laca          0 Material/results_ssp2_bau.gdx
##  9 nip   1     mena          0 Material/results_ssp2_bau.gdx
## 10 nip   1     mexico        0 Material/results_ssp2_bau.gdx
## # ℹ 33,701 more rows
```

Data loading and wrangling

R Basics

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

```
library(tidyverse)
library(gdxtools)
```

The command `library()` loads all the functions from a library.

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

Load a GDX file into R

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

```r
# Define a gdx
dice_gdx <- gdx('Material/dice_2c.gdx')

# Print a summary of the GDX content
dice_gdx
```

```
## <gdx: Material/dice_2c.gdx, 139 symbols>
```

```r
# Obtain a variable and see it as a tibble
dice_gdx["TATM"] |> as_tibble()
```

```
## # A tibble: 100 × 2
##    t     value
##    <chr> <dbl>
##  1 1      0.85
##  2 2      1.02
##  3 3      1.16
##  4 4      1.30
##  5 5      1.42
##  6 6      1.53
##  7 7      1.63
##  8 8      1.73
##  9 9      1.82
## 10 10     1.91
## # ℹ 90 more rows
```

Load a CSV file into R

```r
dice_csv <- read_csv('Material/Dice2016R-091916ap.csv', skip = 6) # returns already a tibble
dice_csv
```

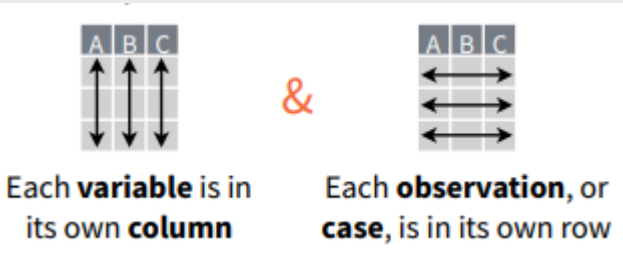
```
## # A tibble: 37 × 101
##    Year       `2015`  `2020`  `2025`  `2030`  `2035`  `2040`  `2045`  `2050`  `2055`
##    <chr>       <dbl>   <dbl>   <dbl>   <dbl>   <dbl>   <dbl>   <dbl>   <dbl>   <dbl>
##  1 Industri… 3.57e+1 3.94e+1 4.29e+1 4.63e+1 4.96e+1 5.27e+1 5.55e+1 5.82e+1 6.06e+1
##  2 Atmosphe… 4.00e+2 4.18e+2 4.38e+2 4.59e+2 4.81e+2 5.04e+2 5.28e+2 5.52e+2 5.78e+2
##  3 Atmosphe… 8.5 e-1 1.02e+0 1.19e+0 1.37e+0 1.55e+0 1.74e+0 1.93e+0 2.13e+0 2.32e+0
##  4 Output N… 1.05e+2 1.25e+2 1.47e+2 1.72e+2 1.98e+2 2.27e+2 2.59e+2 2.92e+2 3.28e+2
##  5 Climate … 1.71e-3 2.44e-3 3.34e-3 4.42e-3 5.68e-3 7.15e-3 8.81e-3 1.07e-2 1.28e-2
##  6 Consumpt… 1.05e+1 1.18e+1 1.33e+1 1.49e+1 1.66e+1 1.85e+1 2.05e+1 2.26e+1 2.49e+1
##  7 Carbon P… 2   e+0 2.21e+0 2.44e+0 2.69e+0 2.97e+0 3.28e+0 3.62e+0 4.00e+0 4.42e+0
##  8 Emission… 2.99e-2 3.23e-2 3.49e-2 3.77e-2 4.08e-2 4.41e-2 4.76e-2 5.15e-2 5.56e-2
##  9 Social c… 3.12e+1 3.73e+1 4.40e+1 5.16e+1 6.00e+1 6.93e+1 7.94e+1 9.05e+1 1.02e+2
## 10 Interest… 5.10e-2 4.98e-2 4.87e-2 4.76e-2 4.66e-2 4.56e-2 4.46e-2 4.36e-2 4.27e-2
## # ℹ 27 more rows
## # ℹ 91 more variables: `2060` <dbl>, `2065` <dbl>, `2070` <dbl>, `2075` <dbl>,
## #   `2080` <dbl>, `2085` <dbl>, `2090` <dbl>, `2095` <dbl>, `2100` <dbl>,
## #   `2105` <dbl>, `2110` <dbl>, `2115` <dbl>, `2120` <dbl>, `2125` <dbl>,
## #   `2130` <dbl>, `2135` <dbl>, `2140` <dbl>, `2145` <dbl>, `2150` <dbl>,
## #   `2155` <dbl>, `2160` <dbl>, `2165` <dbl>, `2170` <dbl>, `2175` <dbl>,
## #   `2180` <dbl>, `2185` <dbl>, `2190` <dbl>, `2195` <dbl>, `2200` <dbl>, …
```

```r
# Correct column name
dice_csv <- dice_csv |> rename(Variable=Year)
```

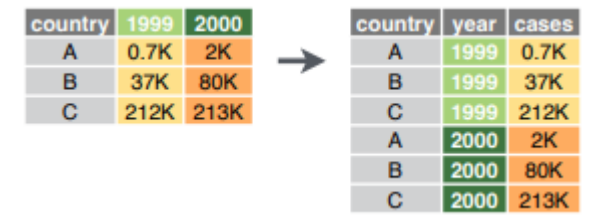
Data wrangling

The raw loaded data are often not directly usable for plotting. It needs to be prepared:

- Transform the data



- Tidy the data (ids and measures columns). If you are not sure, prefer the long version.



country	1999	2000
A	0.7K	2K
B	37K	80K
C	212K	213K

country	year	cases
A	1999	0.7K
B	1999	37K
C	1999	212K
A	2000	2K
B	2000	80K
C	2000	213K

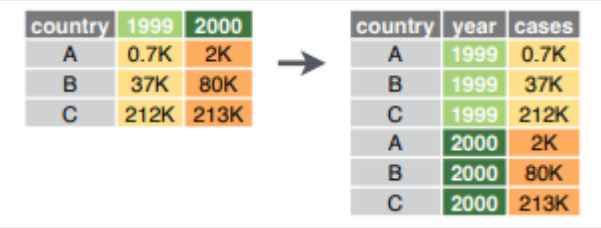
Later, filter the rows and select the columns for your plot.

Reshaping to a long table

```r
# Preview table
head(dice_csv)
```

```
## # A tibble: 6 × 101
##   Variable    `2015`  `2020`  `2025`  `2030`  `2035`  `2040`  `2045`  `2050`  `2055`
##   <chr>        <dbl>   <dbl>   <dbl>   <dbl>   <dbl>   <dbl>   <dbl>   <dbl>   <dbl>
## 1 Industria… 3.57e+1 3.94e+1 4.29e+1 4.63e+1 4.96e+1 5.27e+1 5.55e+1 5.82e+1 6.06e+1
## 2 Atmospher… 4.00e+2 4.18e+2 4.38e+2 4.59e+2 4.81e+2 5.04e+2 5.28e+2 5.52e+2 5.78e+2
## 3 Atmospher… 8.5 e-1 1.02e+0 1.19e+0 1.37e+0 1.55e+0 1.74e+0 1.93e+0 2.13e+0 2.32e+0
## 4 Output Ne… 1.05e+2 1.25e+2 1.47e+2 1.72e+2 1.98e+2 2.27e+2 2.59e+2 2.92e+2 3.28e+2
## 5 Climate D… 1.71e-3 2.44e-3 3.34e-3 4.42e-3 5.68e-3 7.15e-3 8.81e-3 1.07e-2 1.28e-2
## 6 Consumpti… 1.05e+1 1.18e+1 1.33e+1 1.49e+1 1.66e+1 1.85e+1 2.05e+1 2.26e+1 2.49e+1
## # ℹ 91 more variables: `2060` <dbl>, `2065` <dbl>, `2070` <dbl>, `2075` <dbl>,
## #   `2080` <dbl>, `2085` <dbl>, `2090` <dbl>, `2095` <dbl>, `2100` <dbl>,
## #   `2105` <dbl>, `2110` <dbl>, `2115` <dbl>, `2120` <dbl>, `2125` <dbl>,
## #   `2130` <dbl>, `2135` <dbl>, `2140` <dbl>, `2145` <dbl>, `2150` <dbl>,
## #   `2155` <dbl>, `2160` <dbl>, `2165` <dbl>, `2170` <dbl>, `2175` <dbl>,
## #   `2180` <dbl>, `2185` <dbl>, `2190` <dbl>, `2195` <dbl>, `2200` <dbl>,
## #   `2205` <dbl>, `2210` <dbl>, `2215` <dbl>, `2220` <dbl>, `2225` <dbl>, …
```

We want to convert the measure columns into a id column `Year`



Reshaping to a long table

```r
#Let's make a long table we will need it for plotting
mdat_2c = dice_csv ▷
  pivot_longer(!Variable, names_to = "Year")

mdat_2c
```

```
## # A tibble: 3,700 × 3
##    Variable                            Year  value
##    <chr>                               <chr> <dbl>
##  1 Industrial Emissions GTCO2 per year 2015   35.7
##  2 Industrial Emissions GTCO2 per year 2020   39.4
##  3 Industrial Emissions GTCO2 per year 2025   42.9
##  4 Industrial Emissions GTCO2 per year 2030   46.3
##  5 Industrial Emissions GTCO2 per year 2035   49.6
##  6 Industrial Emissions GTCO2 per year 2040   52.7
##  7 Industrial Emissions GTCO2 per year 2045   55.5
##  8 Industrial Emissions GTCO2 per year 2050   58.2
##  9 Industrial Emissions GTCO2 per year 2055   60.6
## 10 Industrial Emissions GTCO2 per year 2060   62.7
## # ℹ 3,690 more rows
```

Note on data wrangling

Function	data.table	tidyverse
From columns to row	`melt()`	`pivot_longer()`
From row to columns	`dcast()`	`pivot_wider()`
merge 2 data.tables	`merge()`	`full_join()`

In this course we will use `tidyverse`, but you can use also functions from the `data.table` package.

For tips in `tidyverse`:

- Transform data: https://raw.githubusercontent.com/rstudio/cheatsheets/main/dplyr.pdf
- Tidy data: https://raw.githubusercontent.com/rstudio/cheatsheets/main/tidyr.pdf

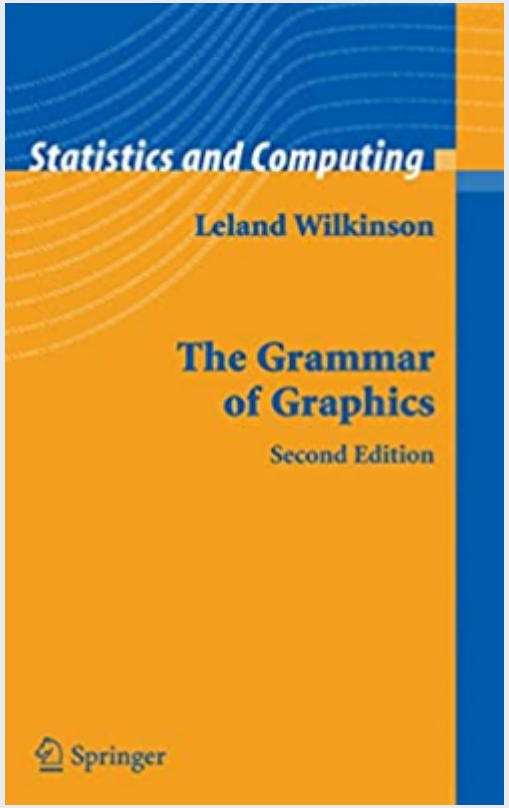
For tips in `data.table`: https://raw.githubusercontent.com/rstudio/cheatsheets/master/datatable.pdf

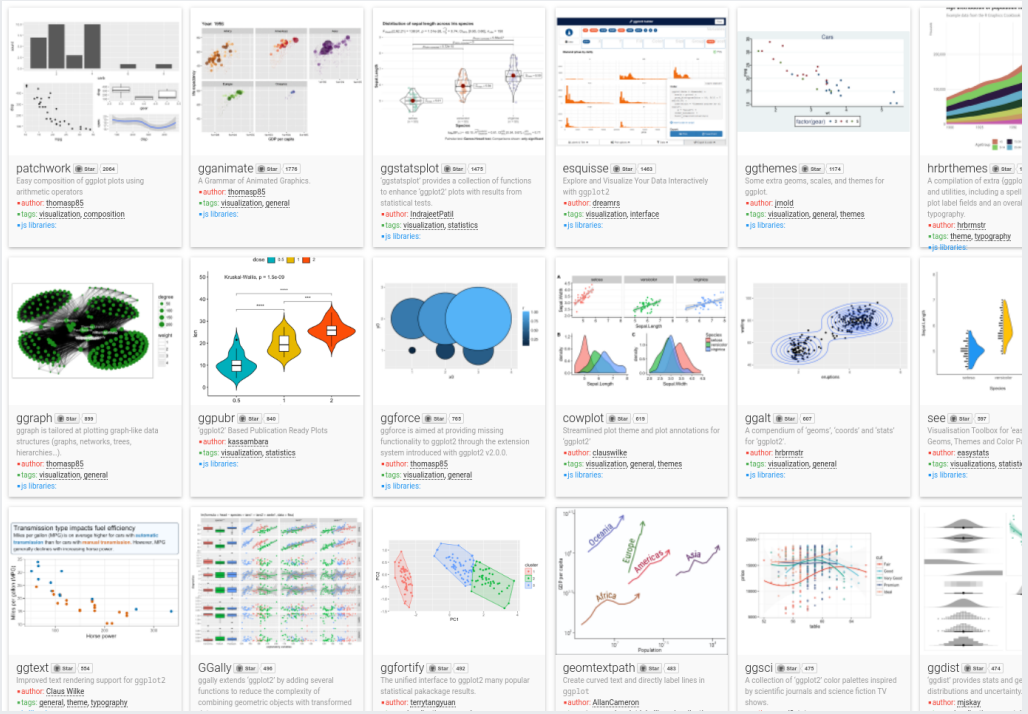
> There are several ways of obtaining the same results.

Data visualization

The `ggplot2` package (included in `tidyverse`)

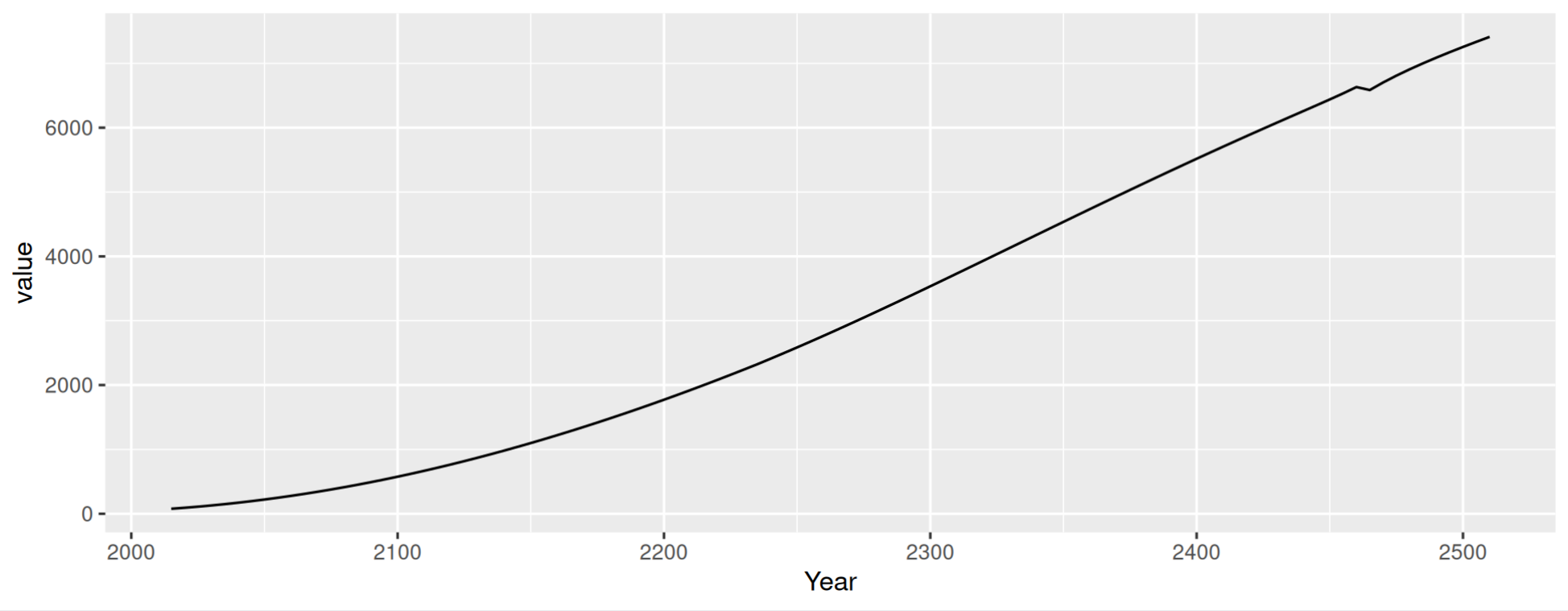
- `ggplot2` implements the grammar of graphics which makes very easy to build a large variety of graphs to explore your data.





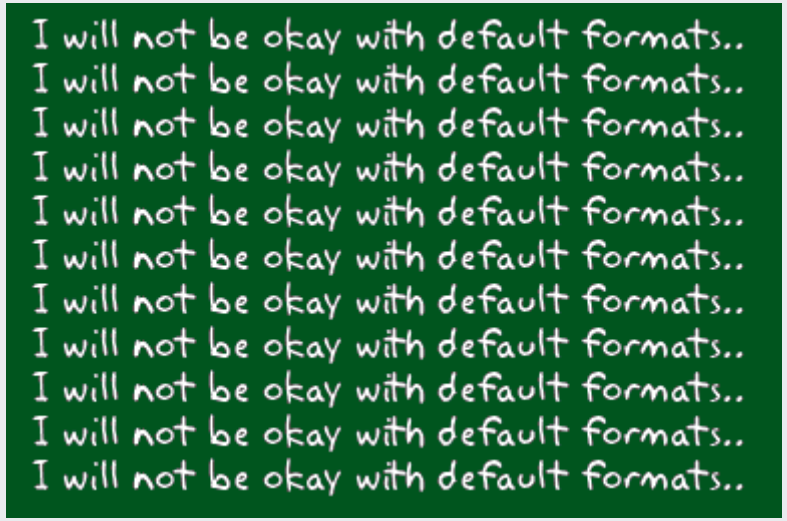
Let's make our first plot (time series)

```
# Year should be numerical
mdat_2c ← mdat_2c ▷ mutate(Year = as.numeric(Year))

# Filter only the variable of interest
ggplot(data = mdat_2c ▷ filter(Variable == 'Consumption'), # DATA
       mapping = aes(x = Year,y = value)) +                # MAPPING
geom_line()                                                # GEOMETRY
```



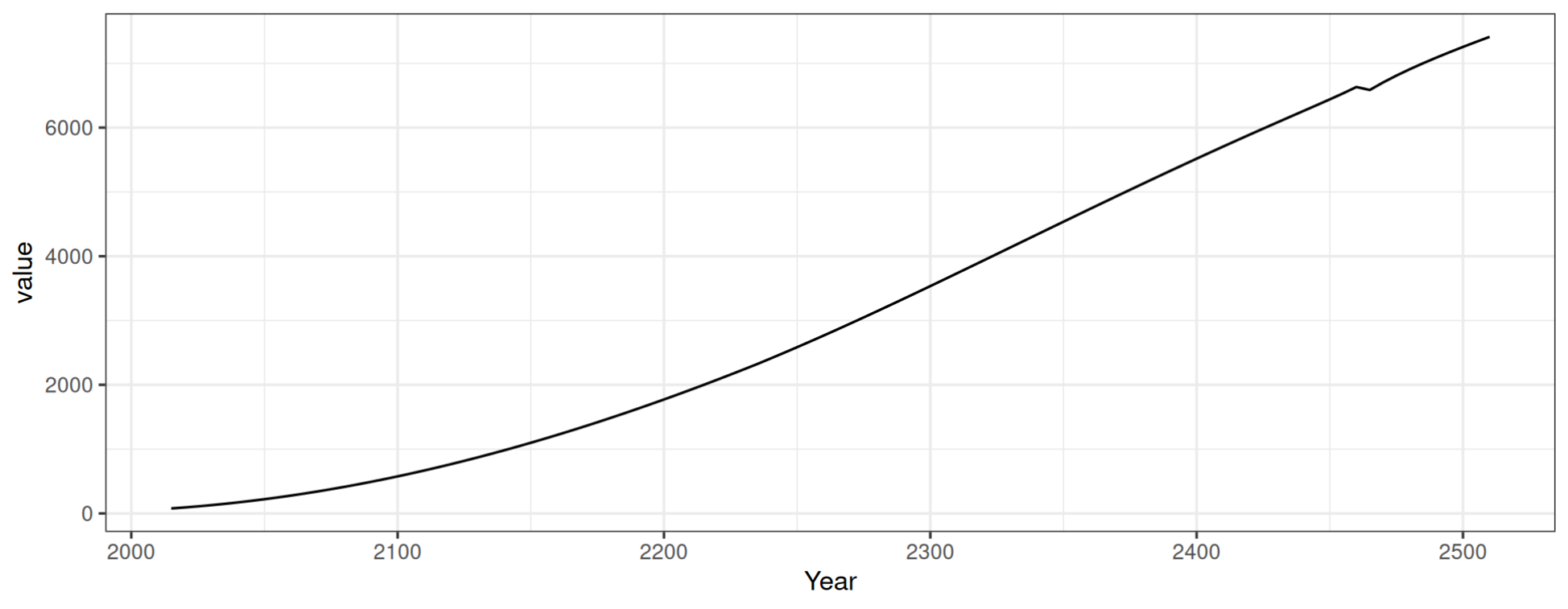
Let's make our first plot (time series)

Take time to design and format your figure



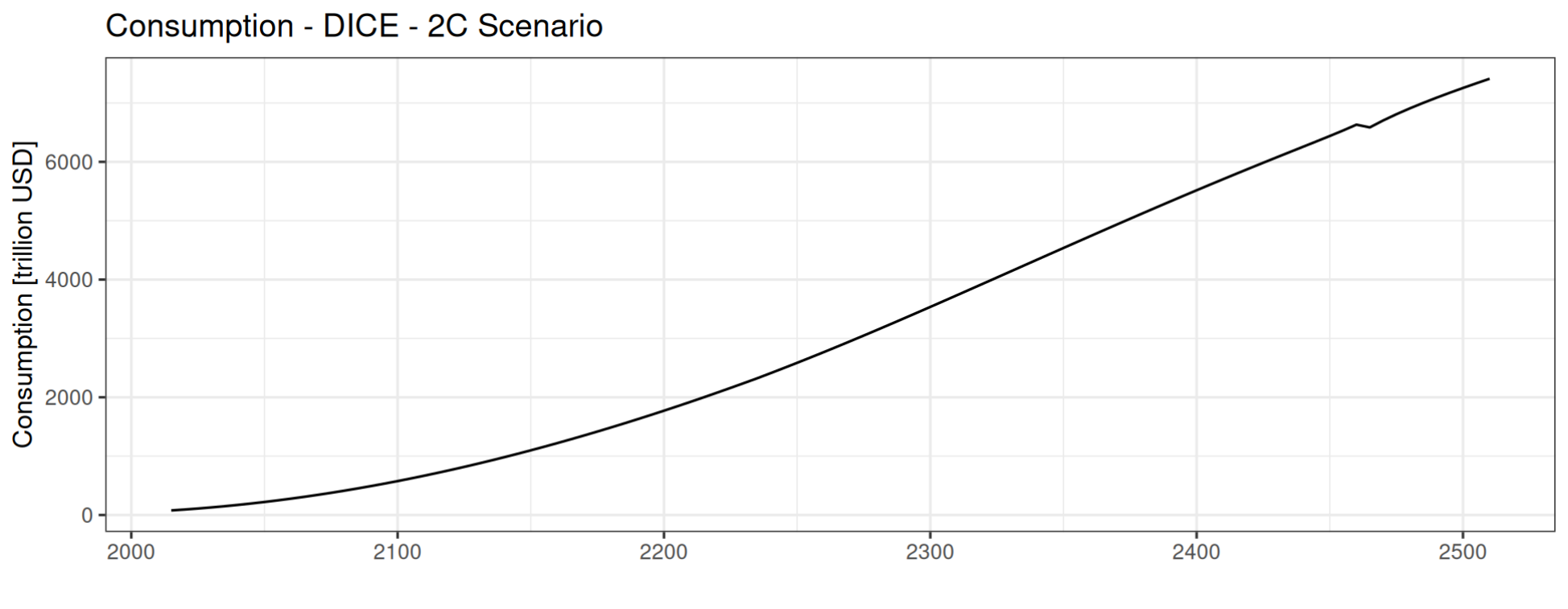
Change the theme

```
ggplot(data = mdat_2c ▷ filter(Variable == 'Consumption'),
       mapping = aes(x = Year,y = value)) +
geom_line() +
theme_bw() # Change overall theme to a more sober and less noisy background
```



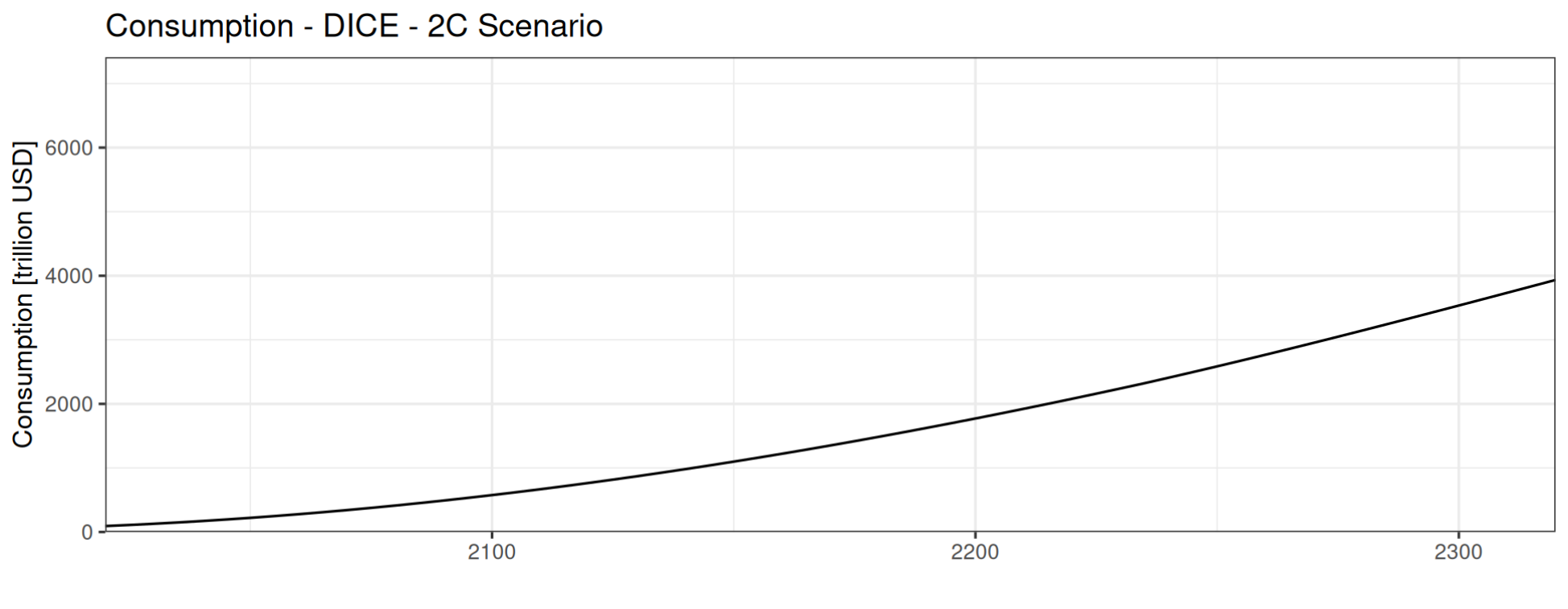
Add a title and labels

```
ggplot(data = mdat_2c ▷ filter(Variable == 'Consumption'),
       mapping = aes(x = Year,y = value)) +
geom_line() +
labs(title = "Consumption - DICE - 2C Scenario", # labs can add subtitle or caption
     x = "",
     y = "Consumption [trillion USD]") +
theme_bw()
```



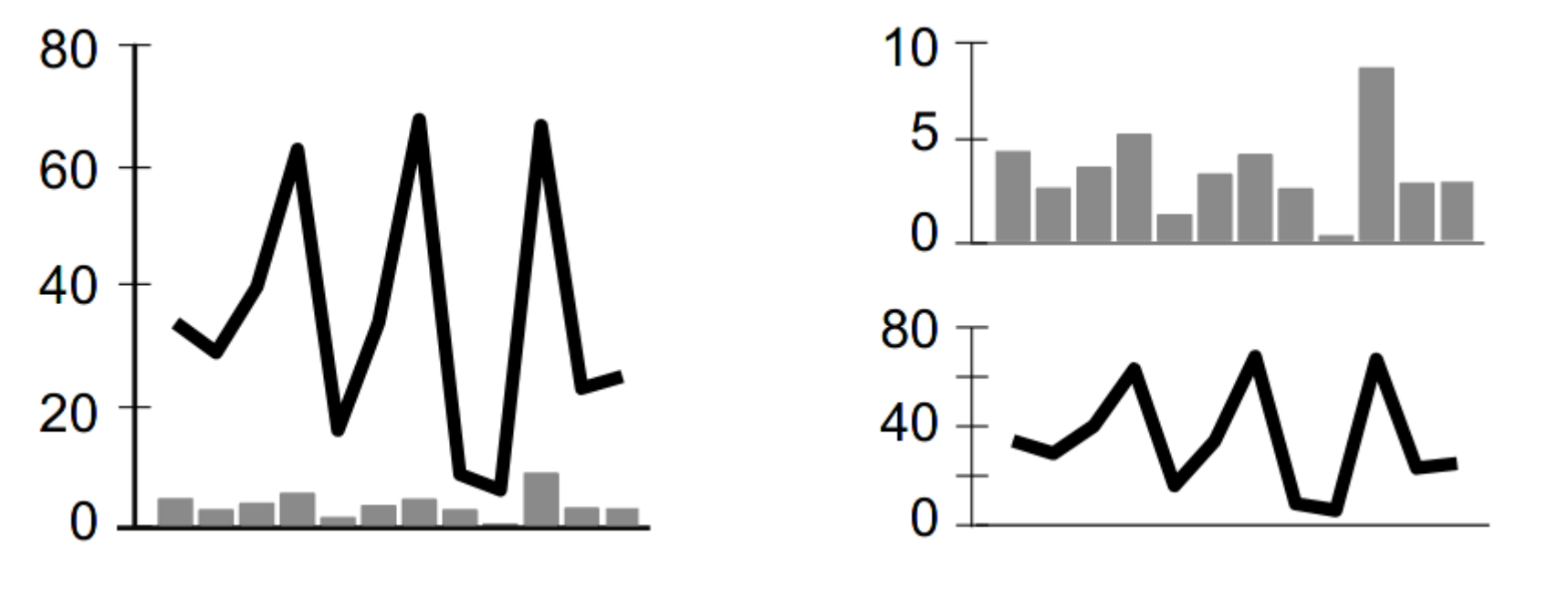
Scale the data

```
ggplot(data = mdat_2c ▷ filter(Variable == 'Consumption'),
       mapping = aes(x = Year,y = value)) +
geom_line() +
labs(title = "Consumption - DICE - 2C Scenario", x = "", y = "Consumption [trillion USD]") +
theme_bw() +
scale_y_continuous(expand = c(0,0), limits = c(0,NA)) +     # Includes 0 in the y-axis
scale_x_continuous(expand = c(0,0), limits = c(2020,2320))  # Zoom-in in the x-axis
```



Let's add more variables

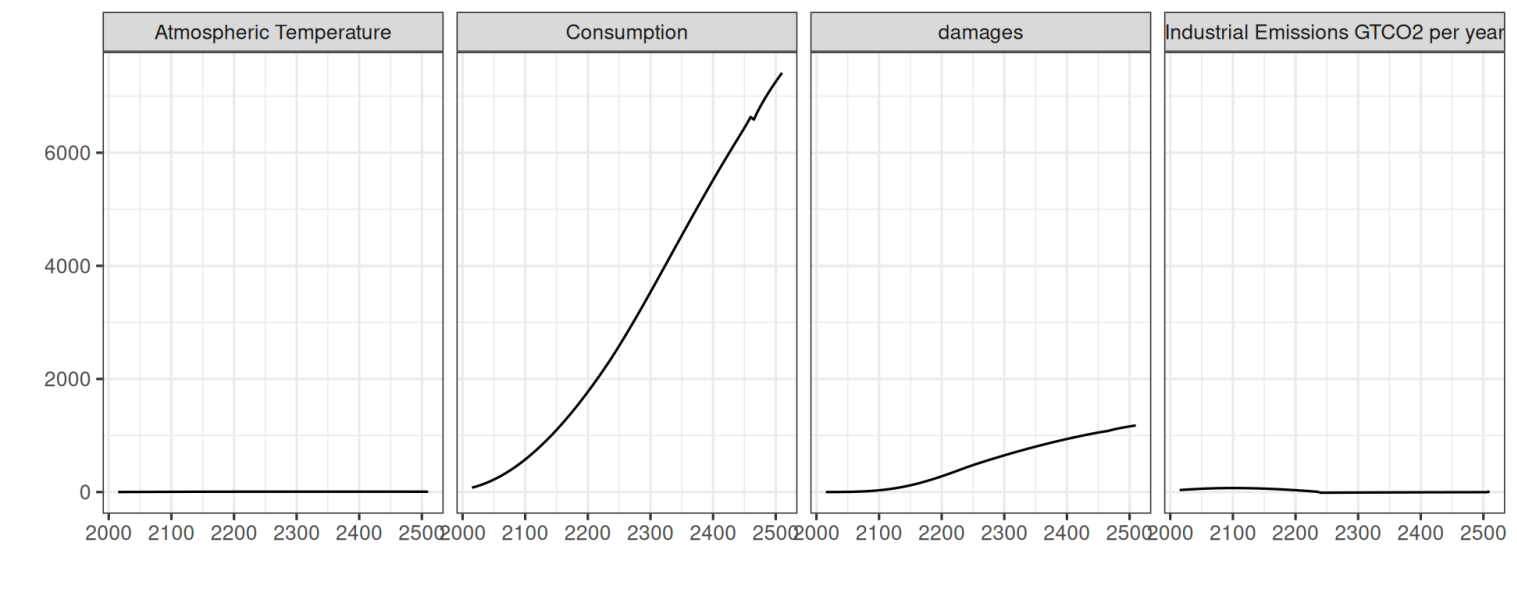
Visualization tip: Do not use mix variables with different scales in the same graph! Separate them into subplots!



source: Kelleher *et al.* (2011)

Use facets

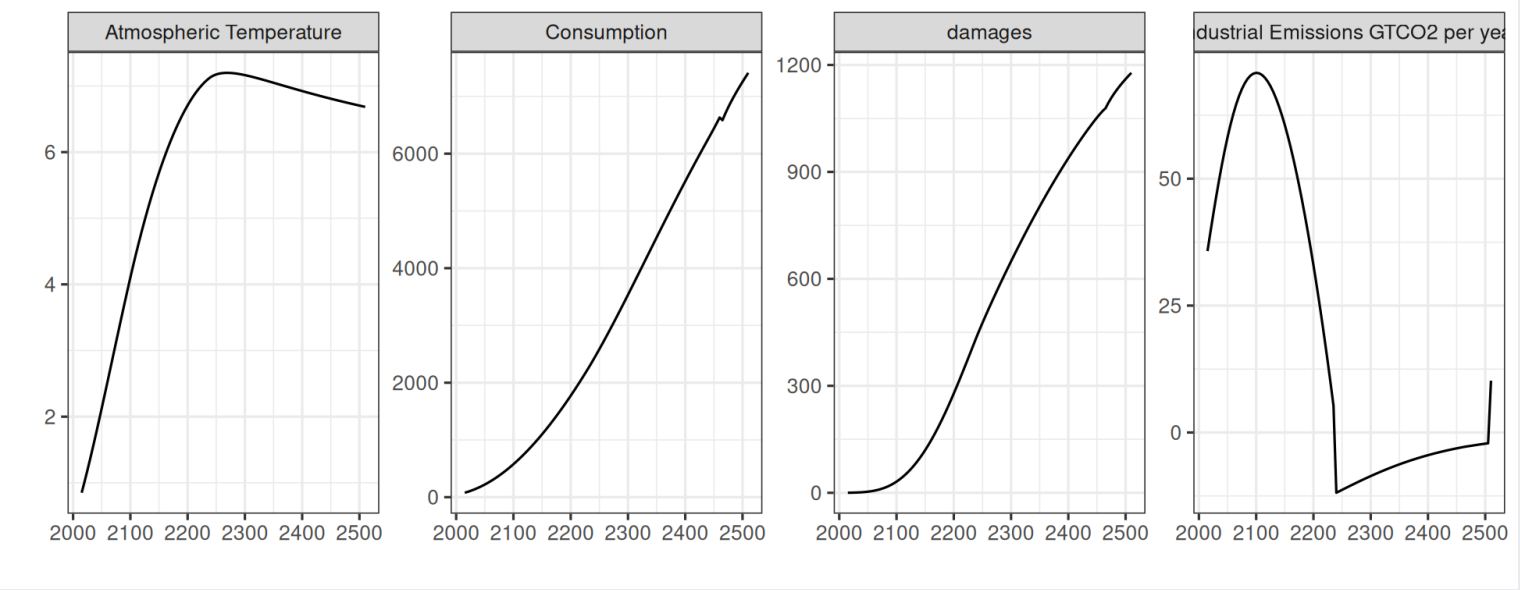
```
vars = c('Consumption','Atmospheric Temperature',
         'Industrial Emissions GTCO2 per year',
         'damages')
ggplot(mdat_2c ▷ filter(Variable %in% vars),
       aes(x = Year, y = value)) +
  geom_line() +
  labs(x = "", y = "") +
  facet_wrap(~Variable, ncol = 4) +
  theme_bw()
```



Use facets, different scales

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

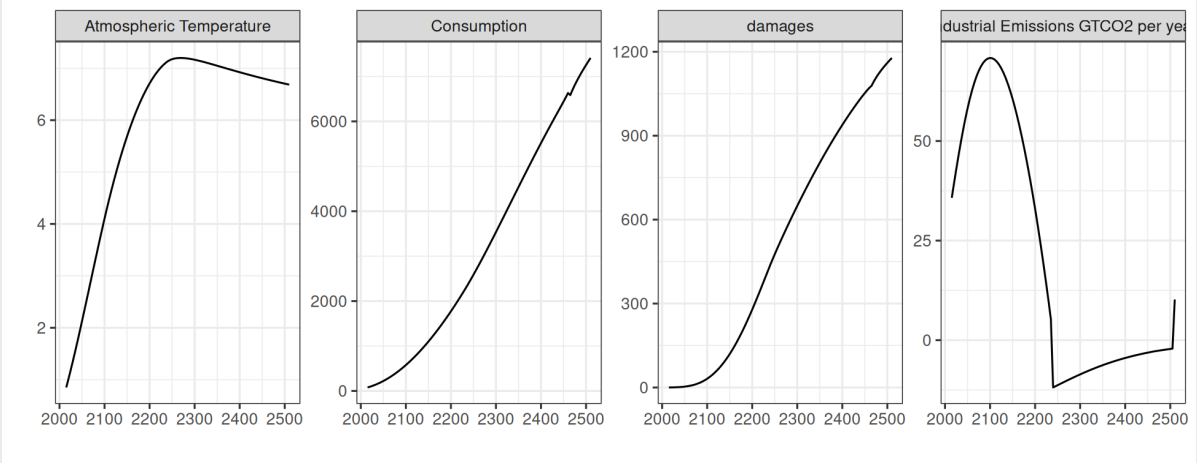
```
vars = c('Consumption','Atmospheric Temperature',
         'Industrial Emissions GTCO2 per year',
         'damages')
ggplot(mdat_2c ▷ filter(Variable %in% vars),
       aes(x = Year, y = value)) +
  geom_line() +
  labs(x = "", y = "") +
  facet_wrap(~Variable, ncol = 4, scales='free') + # ← free scales
  theme_bw()
```



Save your graph

You can store the graph in a variable!

```
p ← ggplot(mdat_2c ▷ filter(Variable %in% vars), aes(x = Year, y = value)) +
  geom_line() +
  labs(x = "", y = "") +
  facet_wrap(~Variable, ncol = 4, scales='free') + # ← free scales
  theme_bw()
p
```




```
ggsave(filename = "Fig1.pdf", plot = p, width = 21, height = 29.7, units = "cm") # A4 format
ggsave(filename = "Fig1.png", plot = p, width = 8, height = 5) # smaller png file
```

Advanced techniques

2D graphs - lines plots

First, read 3 scenarios 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"))
res ← batch_extract("Q_EMI", files = myfiles) # load GHG emissions
# have a look at the structure
str(res) # 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/results_ssp2_bau.gdx" "M
##   ..- attr(*, "gams")= chr ""
```

```
# this grabs the data.frame inside the list GHG$Q_EMI
qemi = res$Q_EMI ▷ as_tibble()
# The element in a list can also be accessed with res[[1]] or res[['Q_EMI']]
```

2D graphs - lines plots

```r
# Have a look now
qemi
```

```
## # A tibble: 50,592 × 5
##    e     t     n         value gdx
##    <chr> <chr> <chr>     <dbl> <chr>
##  1 nip   1     brazil        0 Material/results_ssp2_bau.gdx
##  2 nip   1     canada        0 Material/results_ssp2_bau.gdx
##  3 nip   1     china         0 Material/results_ssp2_bau.gdx
##  4 nip   1     europe        0 Material/results_ssp2_bau.gdx
##  5 nip   1     india         0 Material/results_ssp2_bau.gdx
##  6 nip   1     indonesia     0 Material/results_ssp2_bau.gdx
##  7 nip   1     jpnkor        0 Material/results_ssp2_bau.gdx
##  8 nip   1     laca          0 Material/results_ssp2_bau.gdx
##  9 nip   1     mena          0 Material/results_ssp2_bau.gdx
## 10 nip   1     mexico        0 Material/results_ssp2_bau.gdx
## # ℹ 50,582 more rows
```

```r
qemi <- qemi |>
  mutate(year = as.numeric(t) * 5 + 2000) |> # Transform time period into year
  mutate(scen = basename(gdx)) |>            # Transform the filename into a scenario name
  mutate(scen = str_replace(scen, ".gdx", "")) |>
  mutate(scen = str_replace(scen, "results_ssp2_", ""))

# basename returns the filename without the path
# str_replace replace a given string pattern
```

2D graphs - lines plots

```r
# Update the scenario as factors (ordered set)
qemi <- qemi |>
  mutate(scen = factor(scen, levels = c('bau','ctax50','ctax100')))

# let's have a look again
qemi
```

```
## # A tibble: 50,592 × 7
##    e     t     n         value gdx                          year scen
##    <chr> <chr> <chr>     <dbl> <chr>                         <dbl> <fct>
##  1 nip   1     brazil        0 Material/results_ssp2_bau.gdx  2005 bau
##  2 nip   1     canada        0 Material/results_ssp2_bau.gdx  2005 bau
##  3 nip   1     china         0 Material/results_ssp2_bau.gdx  2005 bau
##  4 nip   1     europe        0 Material/results_ssp2_bau.gdx  2005 bau
##  5 nip   1     india         0 Material/results_ssp2_bau.gdx  2005 bau
##  6 nip   1     indonesia     0 Material/results_ssp2_bau.gdx  2005 bau
##  7 nip   1     jpnkor        0 Material/results_ssp2_bau.gdx  2005 bau
##  8 nip   1     laca          0 Material/results_ssp2_bau.gdx  2005 bau
##  9 nip   1     mena          0 Material/results_ssp2_bau.gdx  2005 bau
## 10 nip   1     mexico        0 Material/results_ssp2_bau.gdx  2005 bau
## # ℹ 50,582 more rows
```

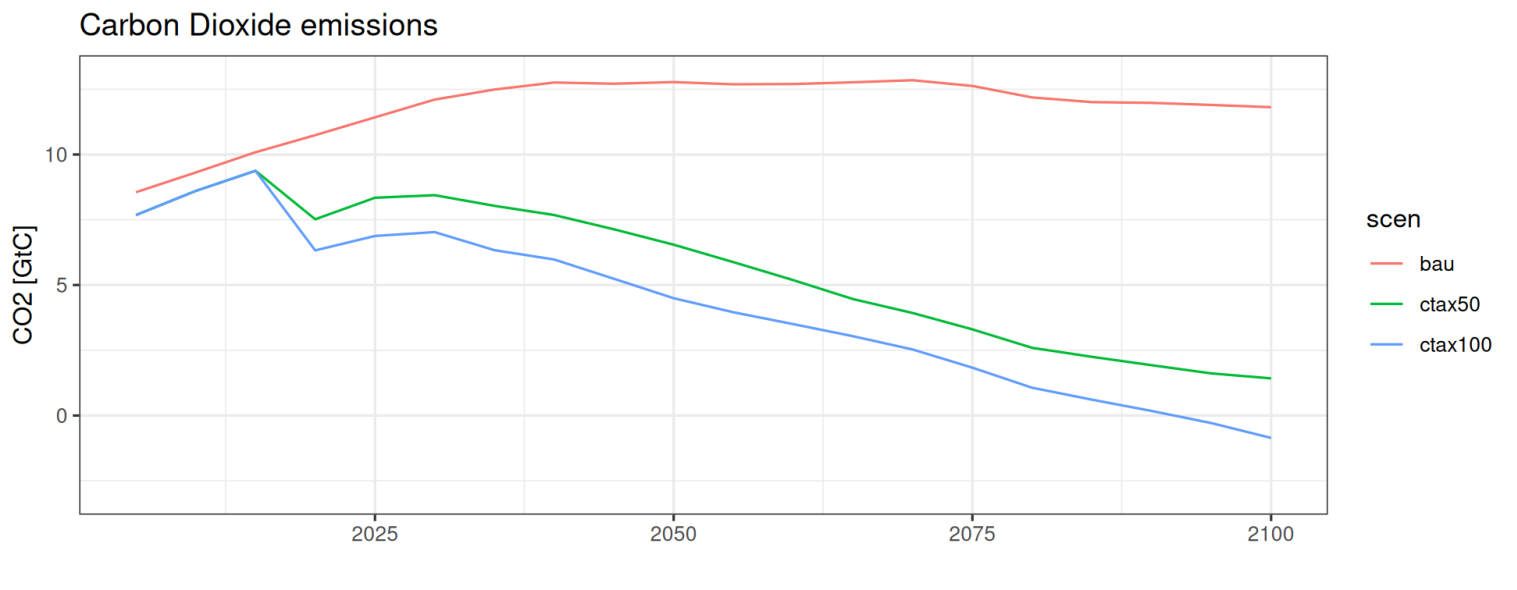
2D graphs - lines plots

```r
# We have 4 id variables, let's reduce it to 3 by aggregation regions into world

wemi <- qemi %>%
  group_by(scen,e,year) %>%
  summarise(value = sum(value))

# have a look

wemi
```

```
## # A tibble: 2,976 × 4
## # Groups:   scen, e [101]
##    scen  e      year   value
##    <fct> <chr> <dbl>   <dbl>
##  1 bau   c2f6   2005 0.00689
##  2 bau   c2f6   2010 0.00923
##  3 bau   c2f6   2015 0.0107
##  4 bau   c2f6   2020 0.0113
##  5 bau   c2f6   2025 0.0113
##  6 bau   c2f6   2030 0.0108
##  7 bau   c2f6   2035 0.00986
##  8 bau   c2f6   2040 0.00870
##  9 bau   c2f6   2045 0.00742
## 10 bau   c2f6   2050 0.00616
## # ℹ 2,966 more rows
```

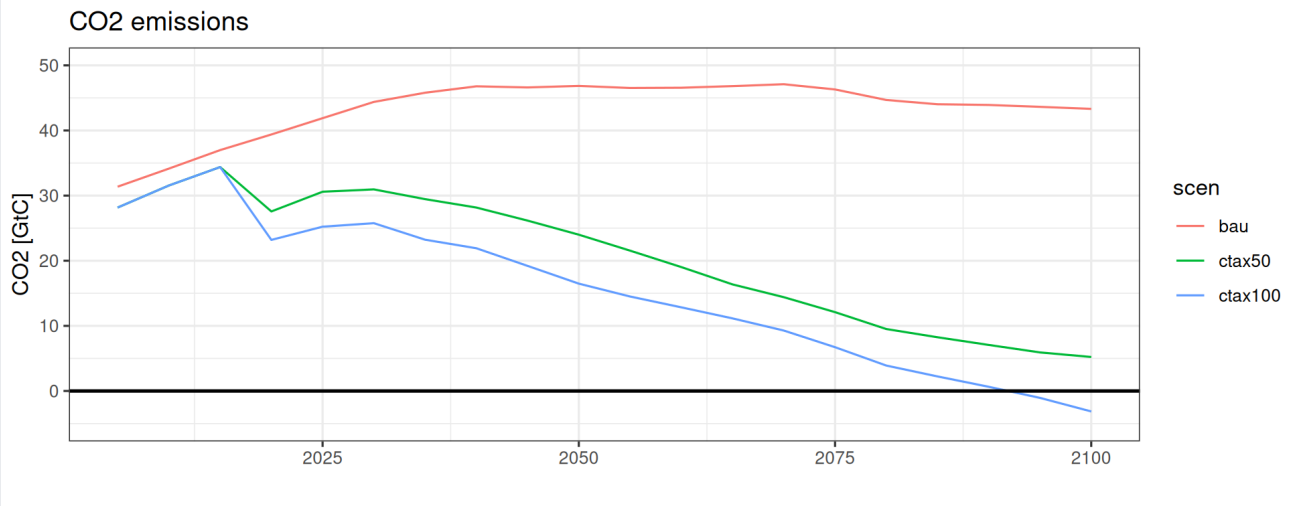
2D graphs - lines plots

```
ggplot(wemi ▷ filter(e == 'co2' & year ≤ 2100),
        aes(x = year, y = value, color = scen)) +
  geom_line() +
  labs(x = "", y = "CO2 [GtC]", title = "Carbon Dioxide emissions") +
  theme_bw() +
  scale_x_continuous(limits=c(2005, 2100)) +
  scale_y_continuous(limits=c(-3, 13))
```



lines plots - meaningful messages

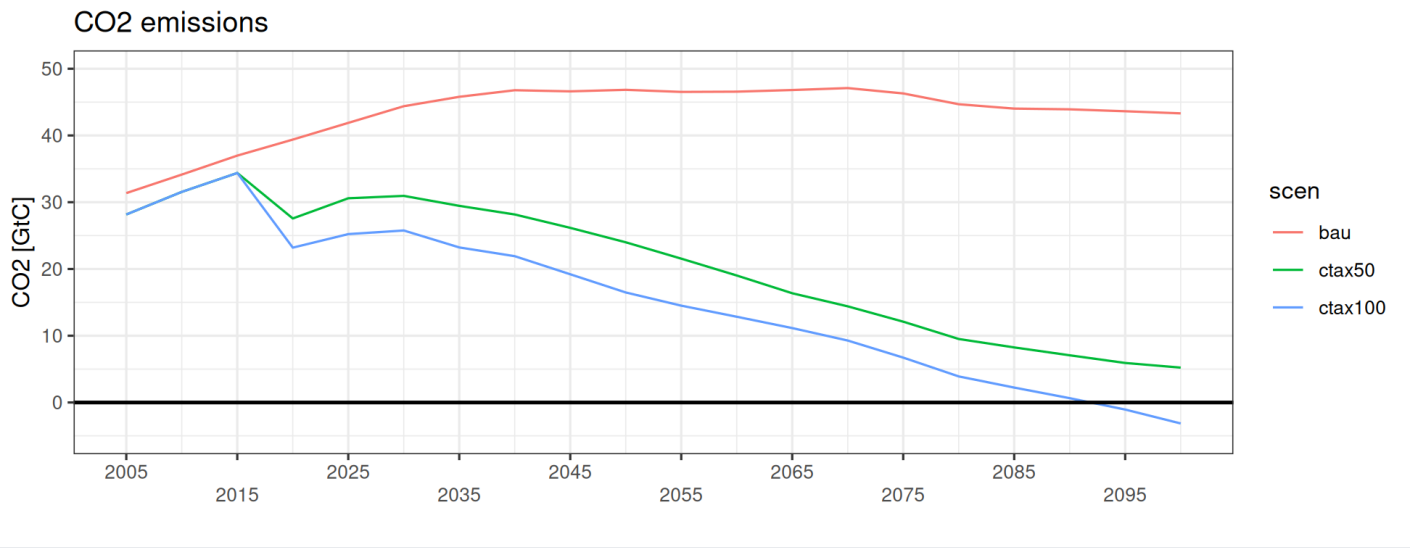
```
# Let's change unit from GtC to GtCO2
wemi ← wemi ▷
  mutate(value = value * 44 / 12)

# Now let's have a look at our data
ggplot(wemi ▷ filter(e == 'co2' & year ≤ 2100),
        aes(x = year, y = value, color = scen)) +
  geom_line() +
  geom_hline(yintercept = 0, color = 'Black', size = 0.8) +
  labs(x = "", y = "CO2 [GtC]", title = "CO2 emissions") +
  theme_bw() +
  scale_x_continuous(limits=c(2005, 2100)) +
  scale_y_continuous(limits=c(-5, 50))
```



2D graphs - lines plots - adjust axis

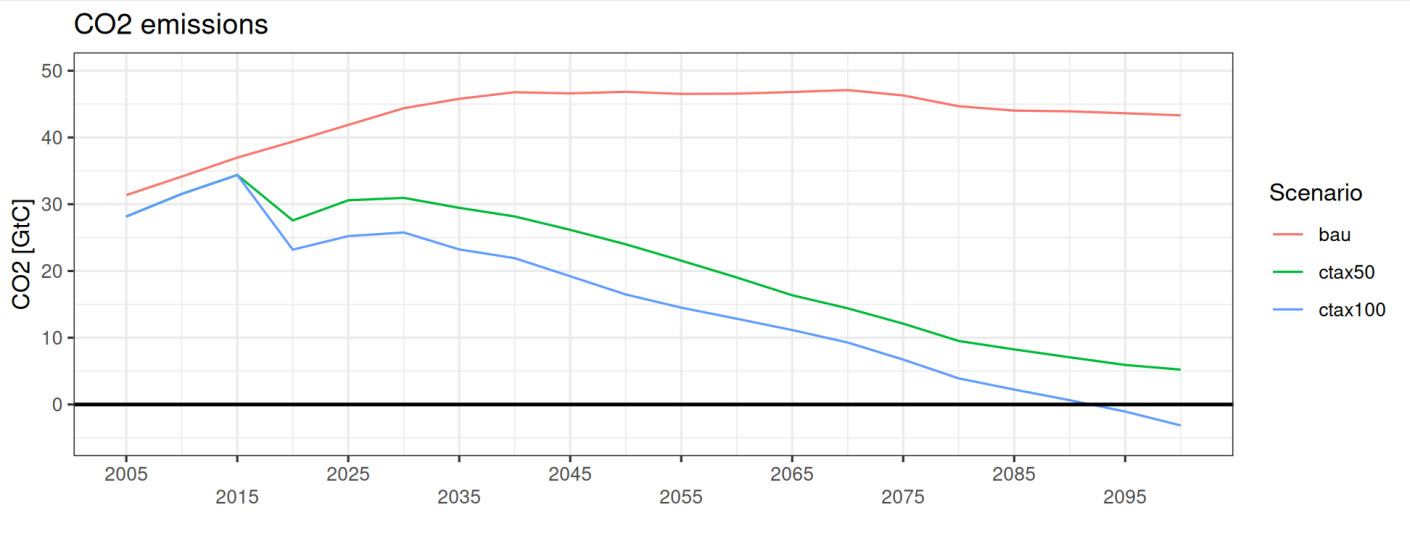
Ease the eye

```
ggplot(wemi ▷ filter(e == 'co2' & year ≤ 2100),
        aes(x = year, y = value, color = scen)) +
  geom_line() +
  geom_hline(yintercept = 0, color = 'Black', size = 0.8) +
  labs(x = "", y = "CO2 [GtC]", title = "CO2 emissions") +
  theme_bw() +
  scale_x_continuous(limits=c(2005, 2100),
                     breaks=seq(2005, 2100,by = 10),    # Define the axis tiks breaks
                     guide = guide_axis(n.dodge = 2)) + # avoid overlapping
  scale_y_continuous(limits=c(-5, 50))
```



Better label for colors

```
ggplot(wemi ▷ filter(e == 'co2' & year ≤ 2100),
        aes(x = year, y = value, color = scen)) +
  geom_line() +
  geom_hline(yintercept = 0, color = 'Black', size = 0.8) +
  labs(x = "", y = "CO2 [GtC]", title = "CO2 emissions") +
  theme_bw() +
  scale_x_continuous(limits=c(2005, 2100),
                     breaks=seq(2005, 2100,by = 10),    # Define the axis tiks breaks
                     guide = guide_axis(n.dodge = 2)) + # avoid overlapping
  scale_y_continuous(limits=c(-5, 50)) +
  scale_color_discrete(name = "Scenario")
```

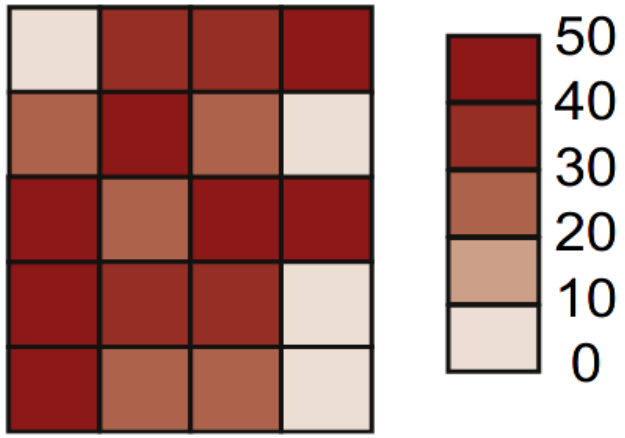


Choose your colors

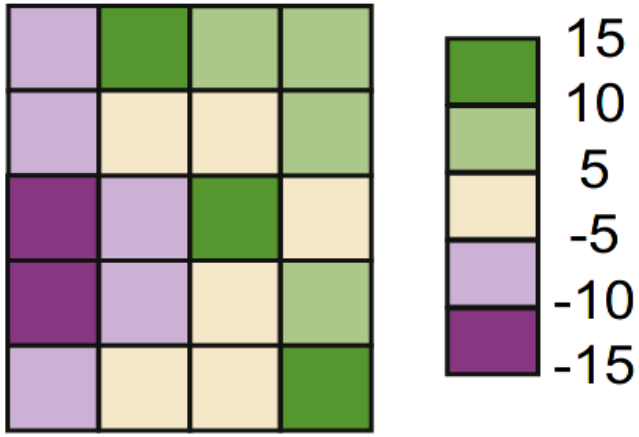
Here are some libraries with color palettes

```
#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



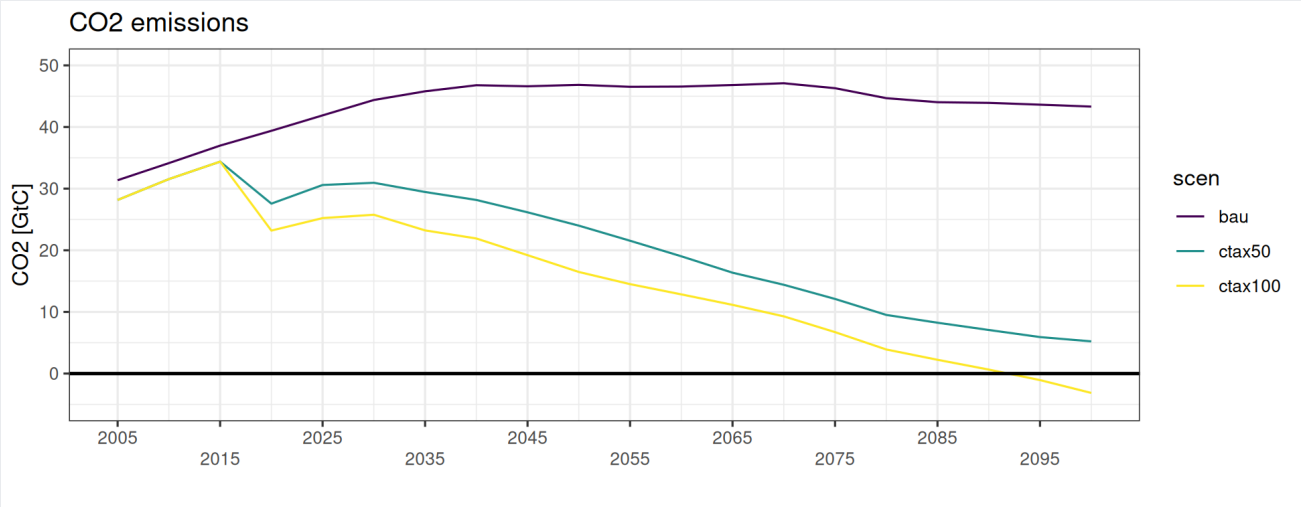
Divergent (zero in the scale)



source: Kelleher *et al.* (2011)

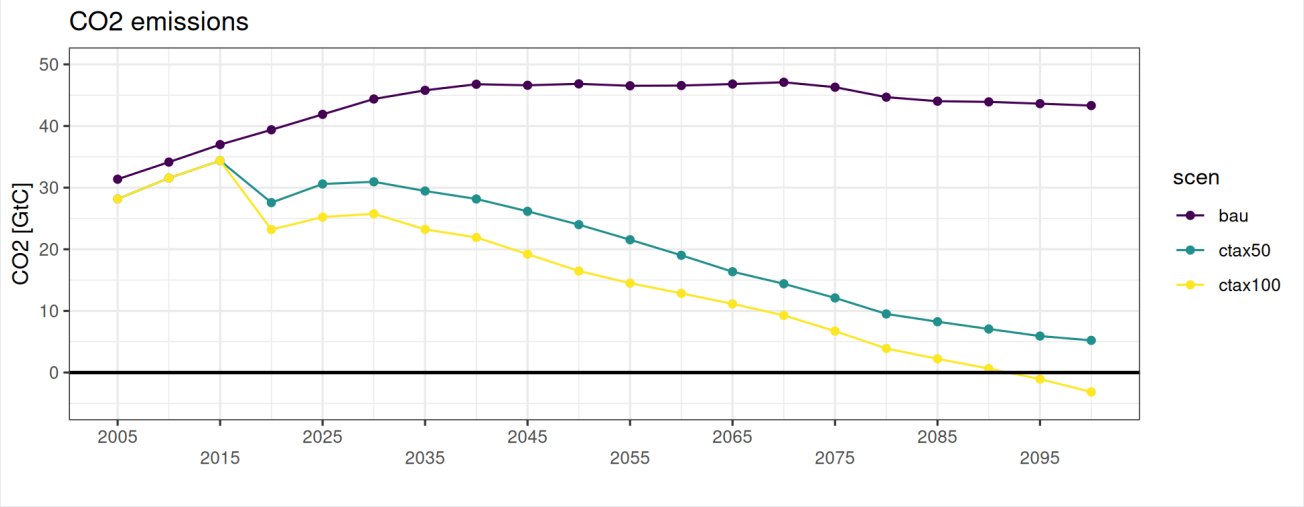
Line plot - Colors

```
ggplot(wemi ▷ filter(e == 'co2' & year ≤ 2100),
        aes(x = year, y = value, color = scen)) +
  geom_line() +
  geom_hline(yintercept = 0, color = 'Black', size = 0.8) +
  labs(x = "", y = "CO2 [GtC]", title = "CO2 emissions") +
  theme_bw() +
  scale_x_continuous(limits=c(2005, 2100),
                     breaks=seq(2005, 2100,by = 10),
                     guide = guide_axis(n.dodge = 2)) +
  scale_y_continuous(limits=c(-5, 50)) +
  scale_color_viridis(discrete = TRUE, option = "D") # use "?" to check the options
```



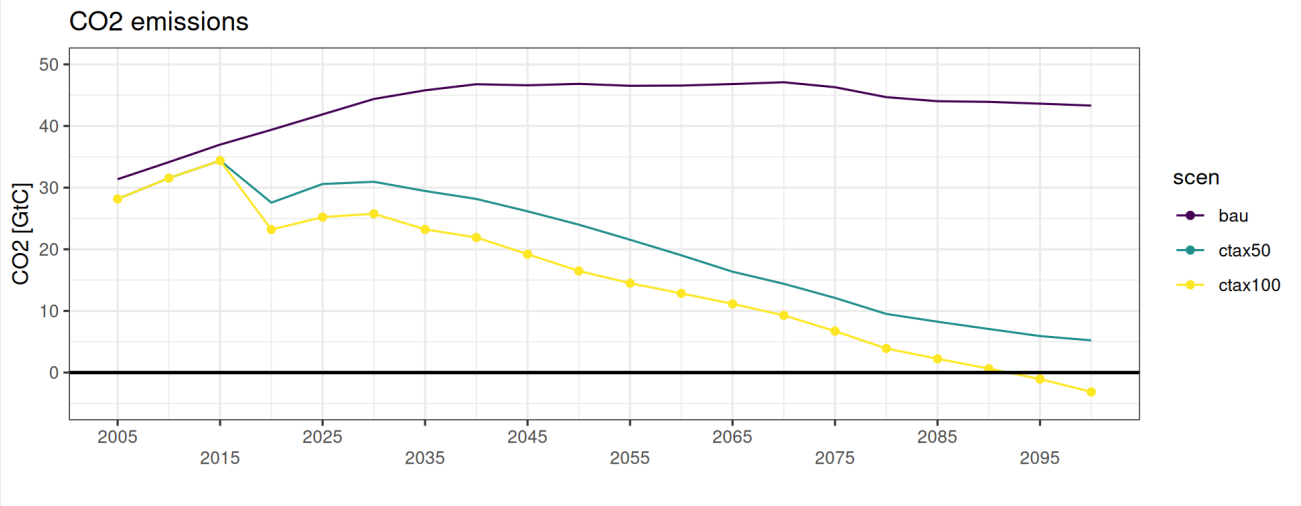
Line plot - Add points

```
ggplot(wemi ▷ filter(e == 'co2' & year ≤ 2100),
        aes(x = year, y = value, color = scen)) +
  geom_line() +
  geom_point() +  # NEW GEOMETRY, SAME DATA AND MAPPING
  geom_hline(yintercept = 0, color = 'Black', size = 0.8) +
  labs(x = "", y = "CO2 [GtC]", title = "CO2 emissions") +
  theme_bw() +
  scale_x_continuous(limits=c(2005, 2100),
                     breaks=seq(2005, 2100,by = 10),
                     guide = guide_axis(n.dodge = 2)) +
  scale_y_continuous(limits=c(-5, 50)) +
  scale_color_viridis(discrete = TRUE, option = "D")
```



Line plot - Subset different data

```
ggplot(wemi ▷ filter(e == 'co2' & year ≤ 2100),
        aes(x = year, y = value, color = scen)) +
  geom_line() +
  geom_point(data = wemi ▷ filter(e == 'co2' & year ≤ 2100 & scen == "ctax100")) +# NEW GEOMETRY, SUBSET BUT SAME MAPI
  geom_hline(yintercept = 0, color = 'Black', size = 0.8) +
  labs(x = "", y = "CO2 [GtC]", title = "CO2 emissions") +
  theme_bw() +
  scale_x_continuous(limits=c(2005, 2100),
                     breaks=seq(2005, 2100,by = 10),
                     guide = guide_axis(n.dodge = 2)) +
  scale_y_continuous(limits=c(-5, 50)) +
  scale_color_viridis(discrete = TRUE, option = "D")
```



Scatter plots - load more data

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

```
pop ← batch_extract("l",files =  myfiles)[[1]] ▷ as_tibble() # Load population

# let's transform time periods into Years
pop ← pop ▷
  mutate(year = as.numeric(t) * 5 + 2000) ▷ # Transform time period into year
  mutate(scen = basename(gdx)) ▷            # Transform the filename into a scenario name
  mutate(scen = str_replace(scen, ".gdx", "")) ▷
  mutate(scen = str_replace(scen, "results_ssp2_", ""))
```

Scatter plots - Merging two data.table objects

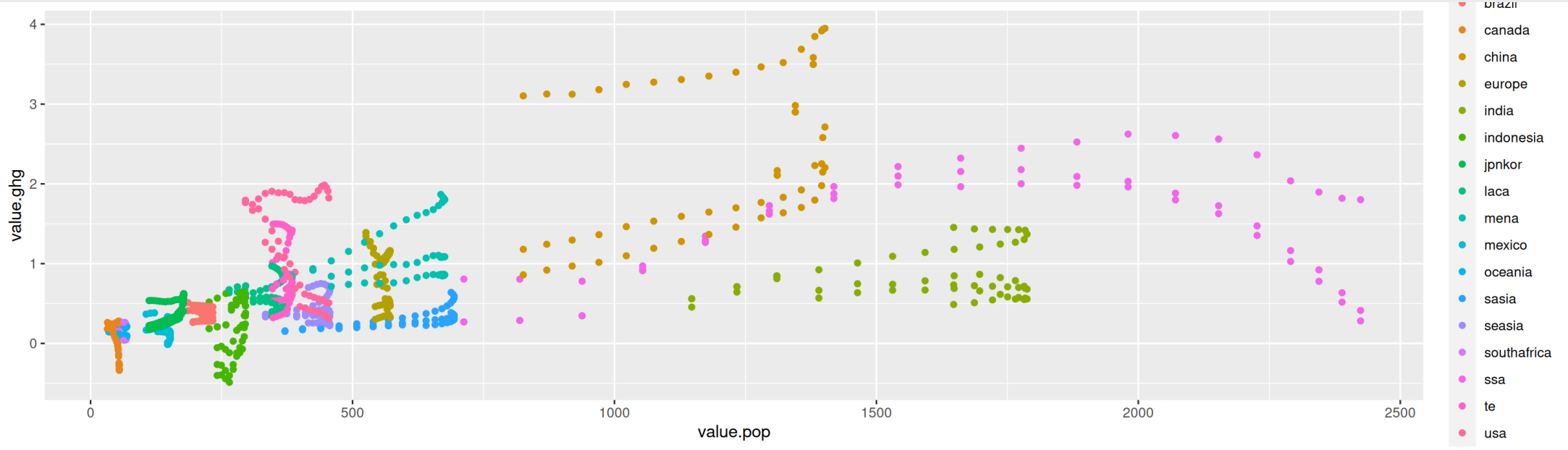
Let's get another variable and merge it with our regional Emissions (GHG)

```
# let's keep 2 emission parameters
 dat = full_join(qemi ▷ filter(e %in% c('kghg','ccs')) ▷ select(-gdx,-t),
                 pop ▷ select(-gdx,-t),
                 by = c("scen","year","n"),
                 suffix = c(".ghg",".pop"))
 # have a look, it's magical
 dat
```

```
## # A tibble: 3,060 × 6
##    e     n         value.ghg  year scen  value.pop
##    <chr> <chr>         <dbl> <dbl> <chr>     <dbl>
##  1 kghg  brazil        0.512  2005 bau       186.
##  2 kghg  canada        0.263  2005 bau        32.3
##  3 kghg  china         2.17   2005 bau      1311.
##  4 kghg  europe        1.34   2005 bau       526.
##  5 kghg  india         0.455  2005 bau      1147.
##  6 kghg  indonesia     0.520  2005 bau       226.
##  7 kghg  jpnkor        0.540  2005 bau       176.
##  8 kghg  laca          0.634  2005 bau       264.
##  9 kghg  mena          0.706  2005 bau       346.
## 10 kghg  mexico        0.167  2005 bau       106.
## # ℹ 3,050 more rows
```

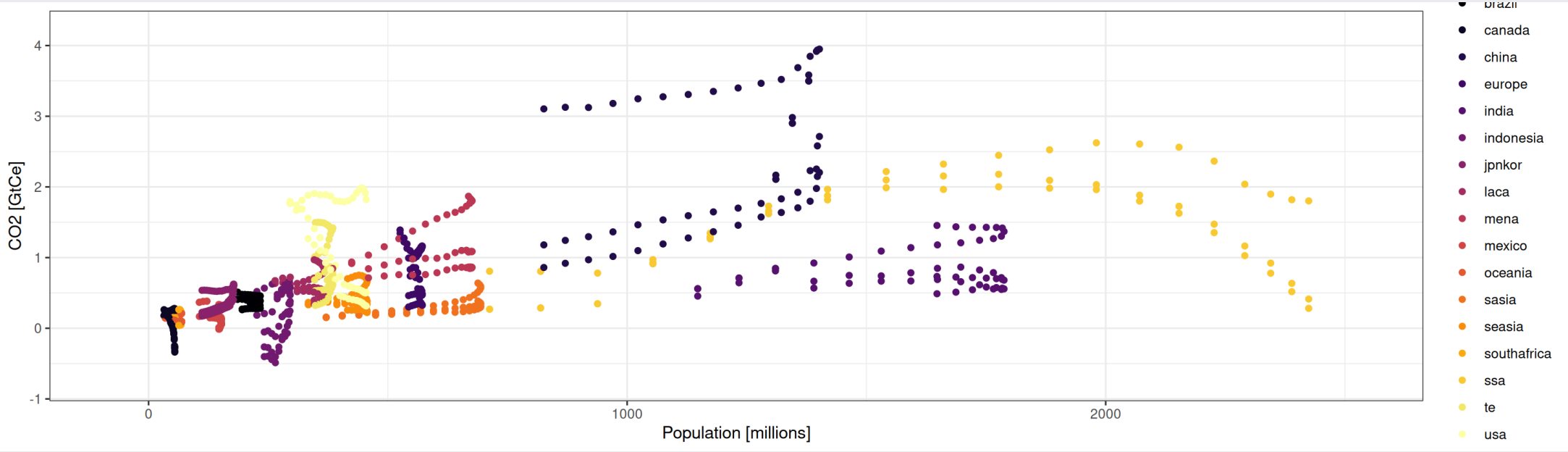
Scatter plots - Adding dimentions

```
ggplot(dat ▷ filter(year < 2100 & e == 'kghg'),
       aes(x = value.pop, y = value.ghg, color = n)) +
 geom_point()
```



Scatter plots - Refuse the defaut options!

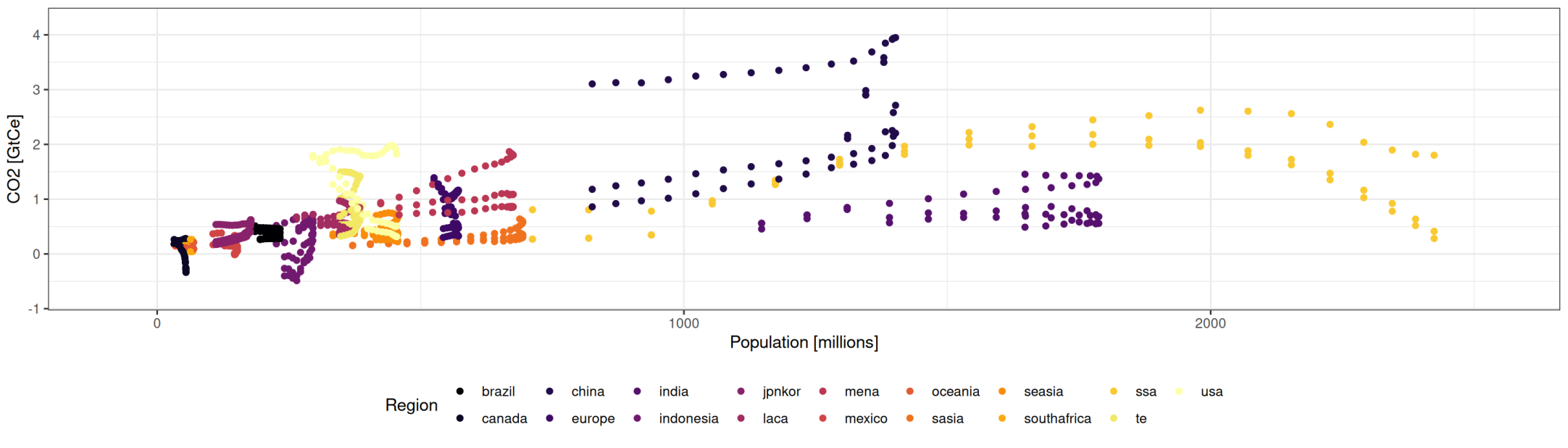
```
ggplot(dat ▷ filter(year < 2100 & e == 'kghg'),
       aes(x = value.pop,y = value.ghg, color = n)) +
  geom_point() +
  scale_x_continuous(name = "Population [millions]",expand = c(0.1, 0.1)) +
  scale_y_continuous(name = "CO2 [GtCe]",expand = c(0.1, 0.1))+
  scale_color_viridis(discrete = TRUE, option = "B", name = "Region") +
  theme_bw()
```



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

Scatter plots - Adjust legend

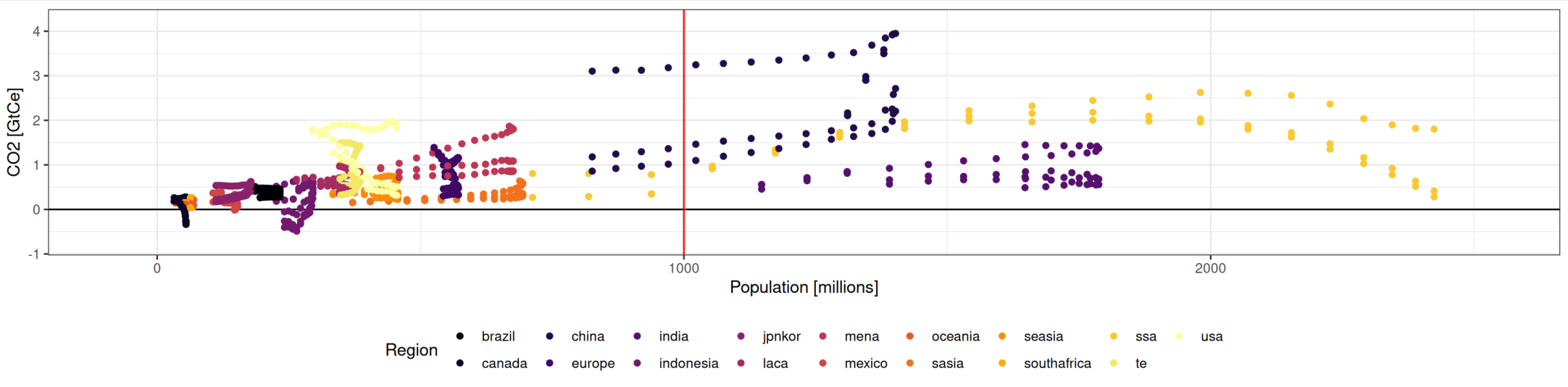
```
ggplot(dat ▷ filter(year < 2100 & e == 'kghg'),
       aes(x = value.pop,y = value.ghg, color = n)) +
  geom_point() +
  scale_x_continuous(name = "Population [millions]",expand = c(0.1, 0.1)) +
  scale_y_continuous(name = "CO2 [GtCe]",expand = c(0.1, 0.1))+
  scale_color_viridis(discrete = TRUE, option = "B", name = "Region") +
  guides(col = guide_legend(ncol = 9)) + # Legend in 9 columns
  theme_bw() +
  theme(legend.position = "bottom")      # Legend in the bottom
```



Scatter plots - Details are important

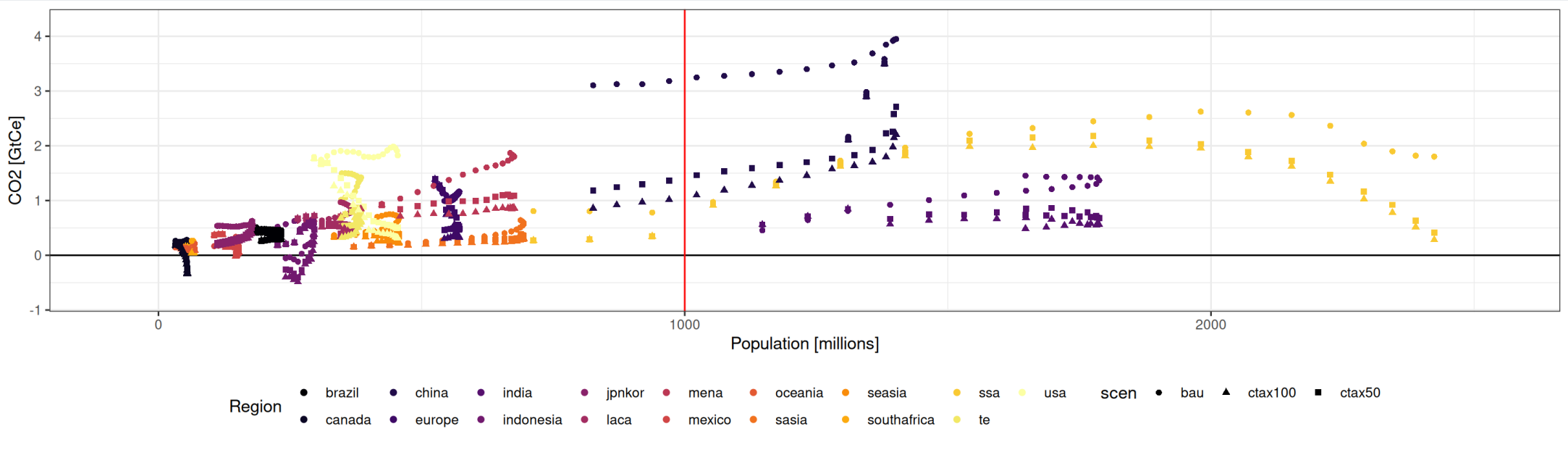
Change names of legend and add guide lines

```
ggplot(dat ▷ filter(year < 2100 & e == 'kghg'),
       aes(x = value.pop,y = value.ghg, color = n)) +
  geom_hline(yintercept = 0) +                    # add a horizontal line at 0
  geom_vline(xintercept = 1000, color = 'red') + # Separate low-high population regions
  geom_point() +
  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", name = "Region") +
  guides(col = guide_legend(ncol = 9)) +
  theme_bw() +
  theme(legend.position = "bottom")
```



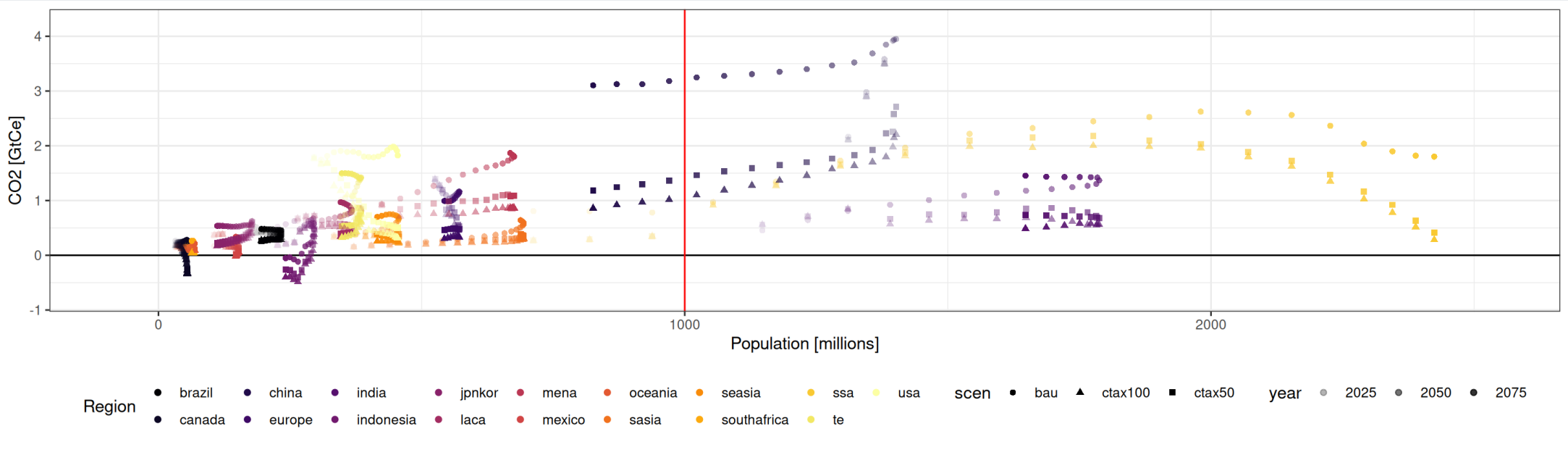
Scatter plots - Add one more dimention

```
ggplot(dat ▷ filter(year < 2100 & e == 'kghg'),
       aes(x = value.pop,y = value.ghg, color = n, shape = scen)) + # add shape
  geom_hline(yintercept = 0) + geom_vline(xintercept = 1000, color = 'red') +
  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", name = "Region") +
  guides(col = guide_legend(ncol = 9)) +
  theme(legend.position = "bottom")
```



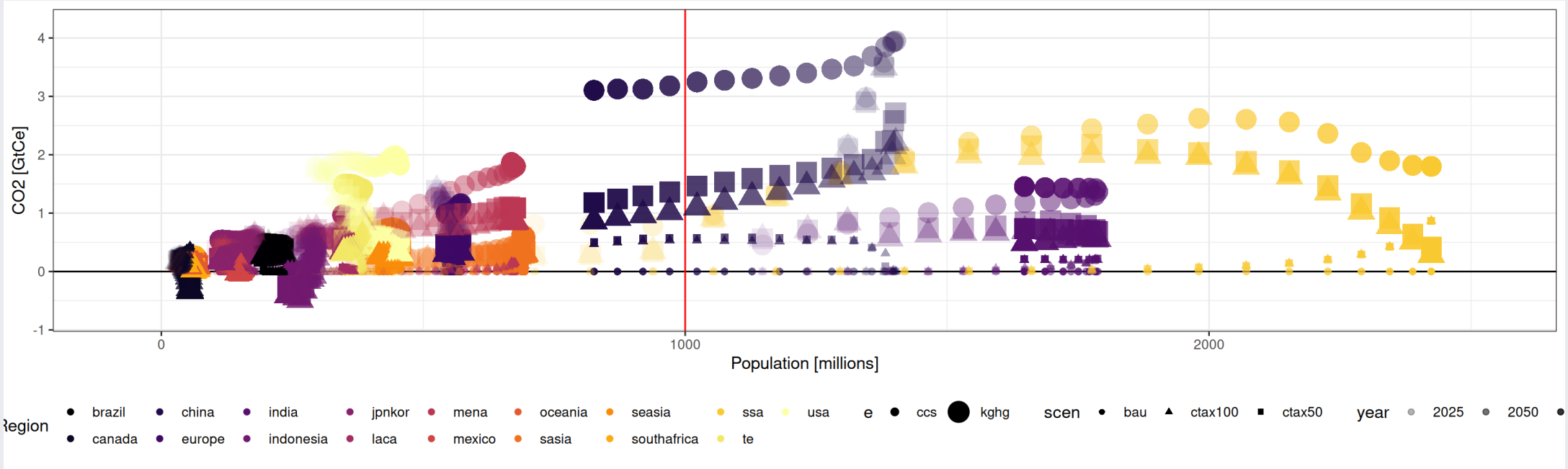
Scatter plots - Add yet another dimention

```
ggplot(dat ▷ filter(year < 2100 & e == 'kghg'),
       aes(x = value.pop,y = value.ghg, color = n, shape = scen, alpha = year))+ # add transparency
  geom_hline(yintercept = 0) + geom_vline(xintercept = 1000, color = 'red') +
  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", name = "Region") +
  guides(col = guide_legend(ncol = 9)) +
  theme(legend.position = "bottom")
```



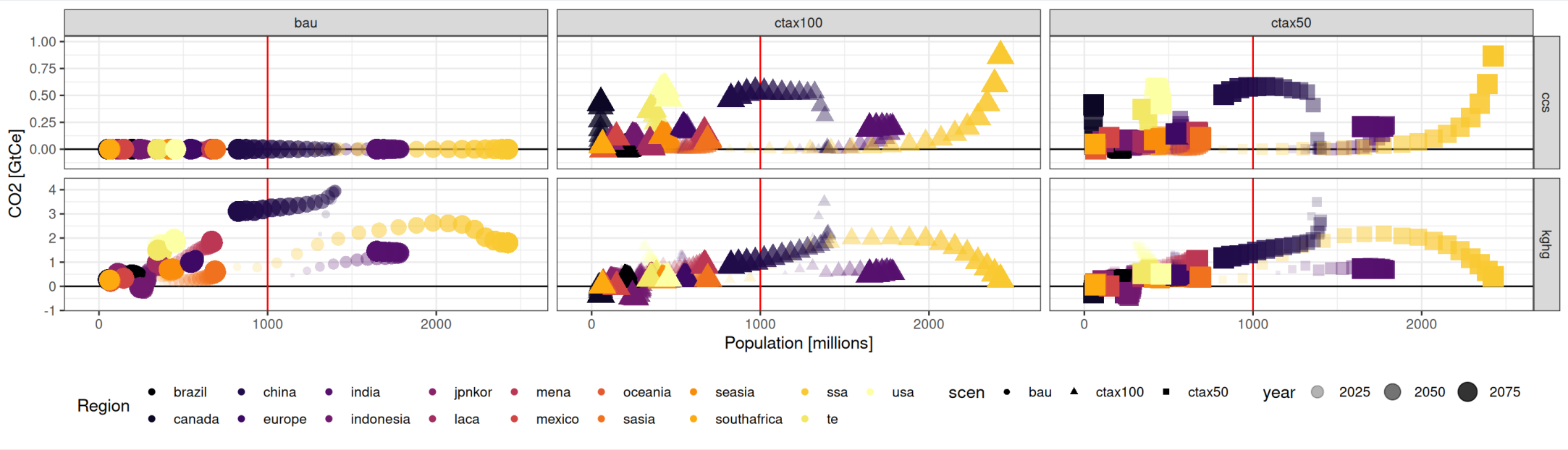
Scatter plots - and one more ... too many!

```
ggplot(dat ▷ filter(year < 2100),
       aes(x = value.pop,y = value.ghg, color = n, shape = scen, alpha = year, size = e)) + # add size with 'e'
  geom_hline(yintercept = 0) + geom_vline(xintercept = 1000, color = 'red') +
  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", name = "Region") +
  guides(col = guide_legend(ncol = 9)) +
  theme(legend.position = "bottom")
```



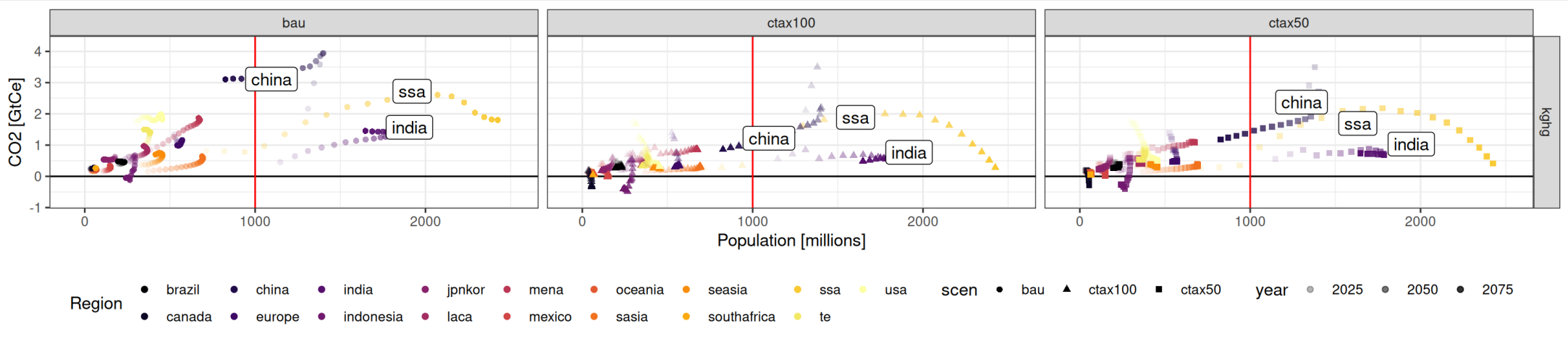
Scatter plots - Let's exagerate

```
ggplot(dat ▷ filter(year < 2100),
       aes(x = value.pop,y = value.ghg, color = n, shape = scen, alpha = year, size = year)) + # add size with 'e'
  geom_hline(yintercept = 0) + geom_vline(xintercept = 1000, color = 'red') +
  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", name = "Region") +
  facet_grid(e~scen, scales='free') + # Add facets
  guides(col = guide_legend(ncol = 9)) +
  theme(legend.position = "bottom")
```



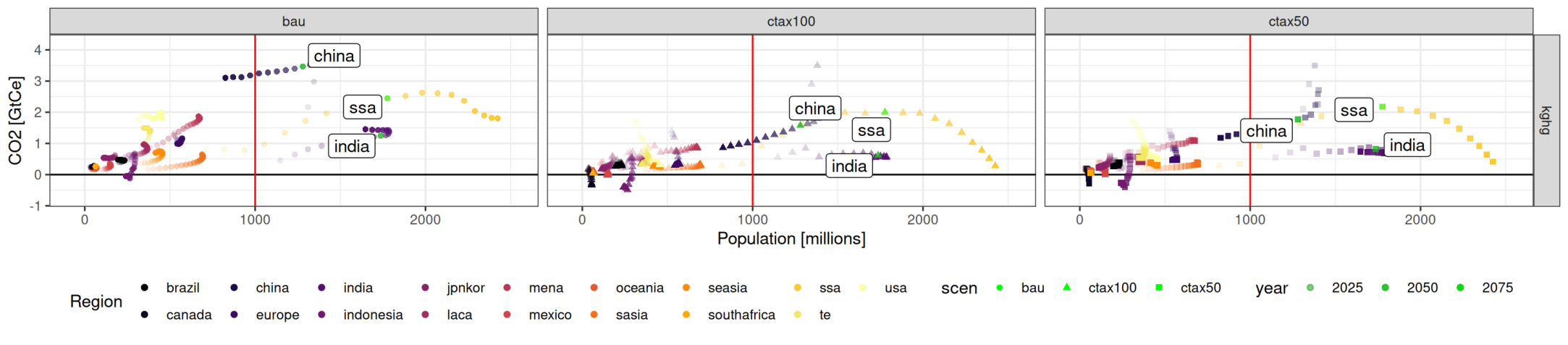
Scatter plots - help the reader

```
library(ggrepel)
ggplot(dat ▷ filter(year < 2100 & e == "kghg"),
       aes(x = value.pop,y = value.ghg, color = n, shape = scen, alpha = year)) +
  geom_hline(yintercept = 0) + geom_vline(xintercept = 1000, color = 'red') + geom_point() + theme_bw() +
  geom_label_repel(aes(label = n),
                   dat ▷ filter(year == 2050 & value.pop > 1000 & e == 'kghg'),
                   color = 'black', alpha = 1) + # Add labels
  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", name = "Region") +
  facet_grid(e~scen, scales='free') + guides(col = guide_legend(ncol = 9)) + theme(legend.position = "bottom")
```



Scatter plots - Draw attention to ...

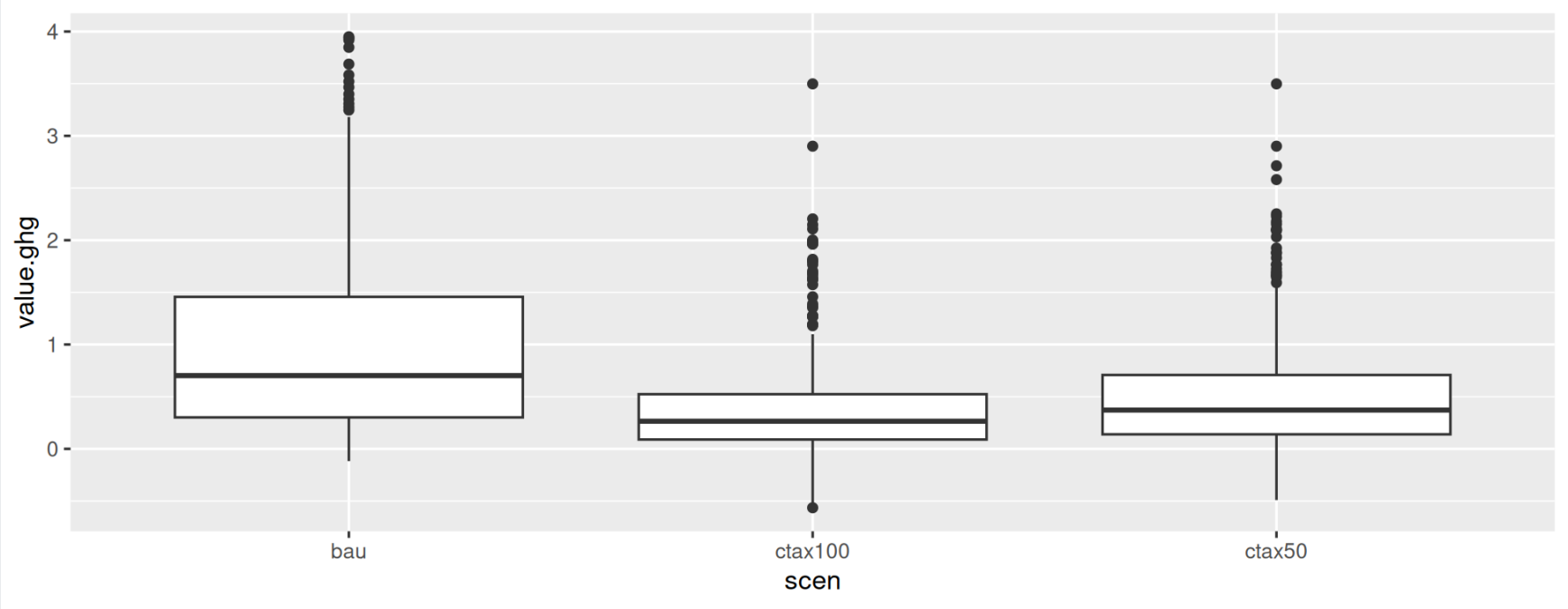
```
ggplot(dat ▷ filter(year < 2100 & e == "kghg"),
       aes(x = value.pop,y = value.ghg, color = n, shape = scen, alpha = year)) +
  geom_hline(yintercept = 0) + geom_vline(xintercept = 1000, color = 'red') + geom_point() + theme_bw() +
  geom_point(data = dat ▷ filter(year == 2050 & value.pop > 1000 & e == 'kghg'),
             color='green')+ # Emphasize a few points
  geom_label_repel(aes(label = n), dat ▷ filter(year == 2050 & value.pop > 1000 & e == 'kghg'),
                   color = 'black', alpha = 1) +
  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", name = "Region") +
  facet_grid(e~scen, scales='free') +
  guides(col = guide_legend(ncol = 9)) +
  theme(legend.position = "bottom")
```



Box plots - Plotting distributions

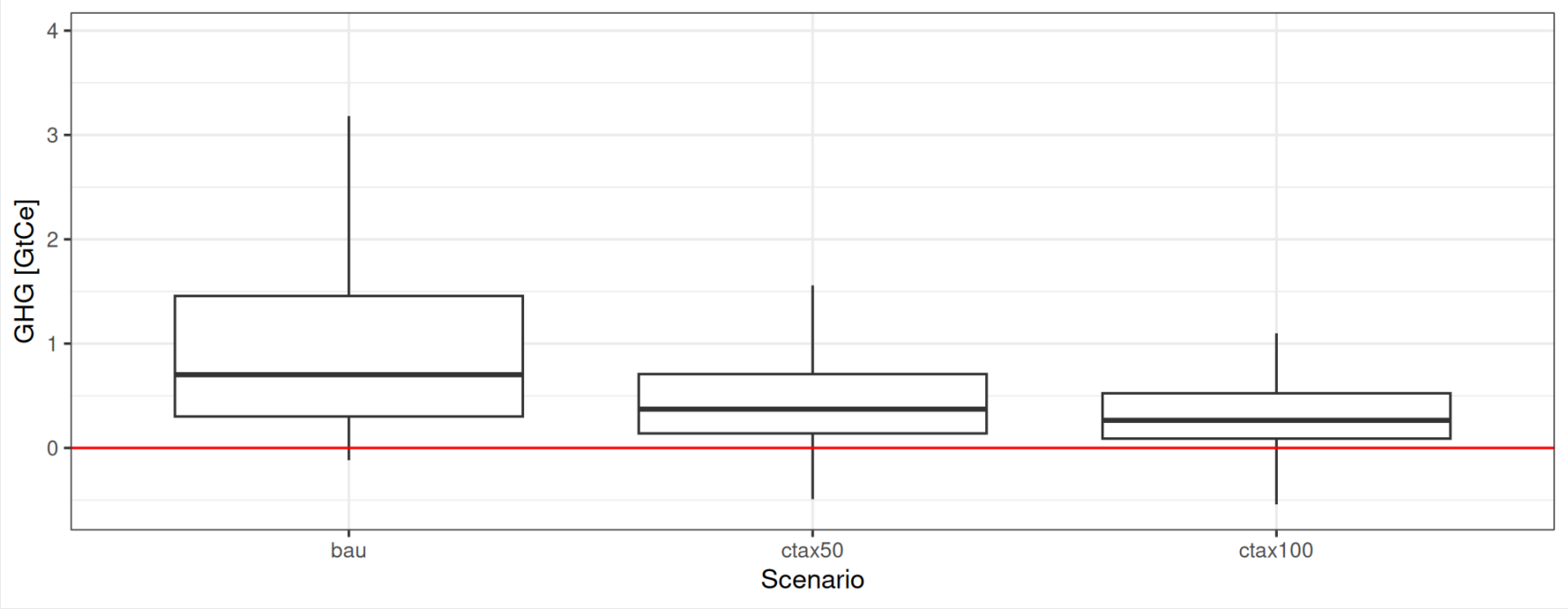
When mean or median are not enough

```
ggplot(dat ▷ filter(e=='kghg'),
       aes(x = scen, y = value.ghg)) +
  geom_boxplot()
```



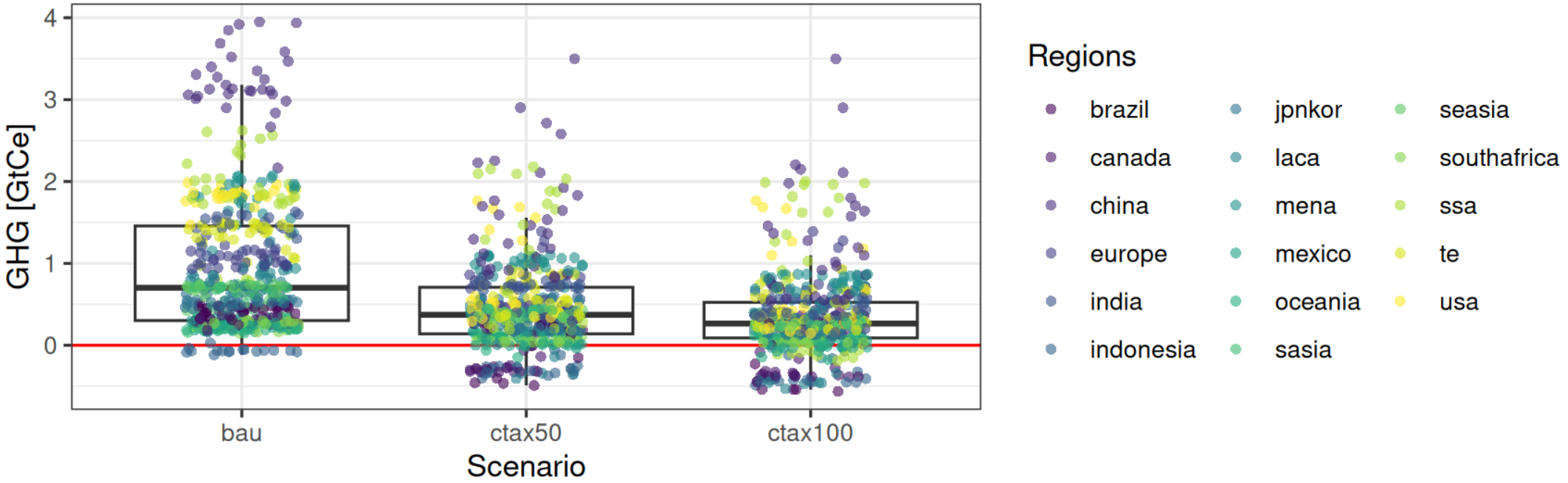
Box plots - typical retouch..

```
# Update the scenario as factors (ordered set)
dat ← dat ▷
  mutate(scen = factor(scen, levels = c('bau','ctax50','ctax100')))

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



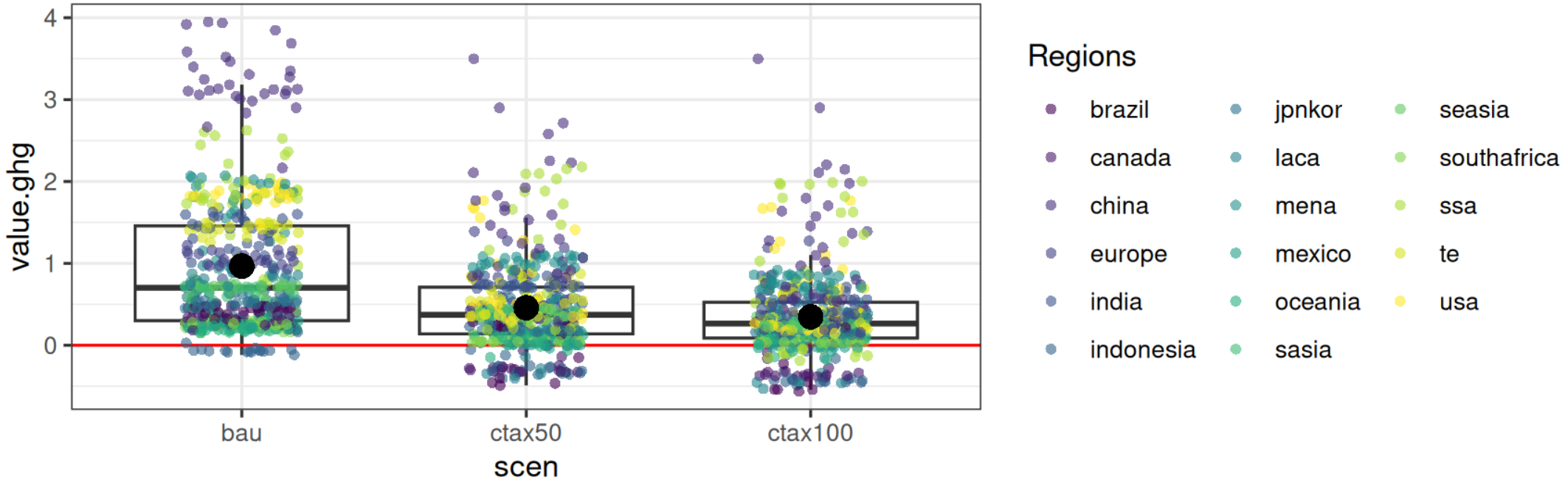
Box plots - add the underlying observations

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

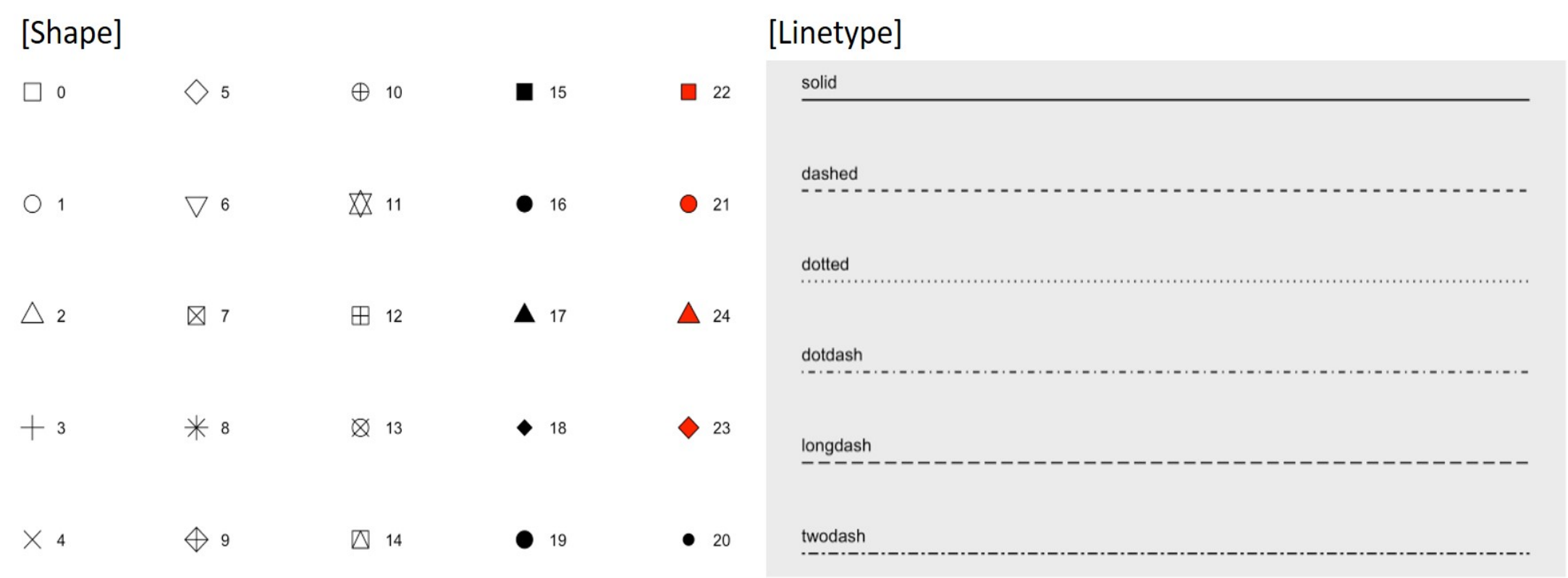


Box plots - add more infomation

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



Shapes and linetypes



Maps - Showing regional information

We need to prepare the data first

```
# import the WITCH model regional definition
wreg ← read_csv('Material/mapwitch17.csv')

# Country name tools
library(countrycode)

# transforms ISO codes into country names
wreg ← wreg ▷
  mutate(region = countrycode(ISO, origin = 'iso3c', destination = 'country.name'))

# Correcting some mismatches
#wreg[ISO=='GBR']$region = 'UK'
#wreg[ISO=='USA']$region = 'USA'
wreg
```

```
## # A tibble: 250 × 3
##    n           ISO   region
##    <chr>       <chr> <chr>
##  1 canada      CAN   Canada
##  2 canada      SPM   St. Pierre & Miquelon
##  3 jpnkor      JPN   Japan
##  4 jpnkor      KOR   South Korea
##  5 oceania     NZL   New Zealand
##  6 oceania     AUS   Australia
##  7 indonesia   IDN   Indonesia
##  8 southafrica ZAF   South Africa
##  9 brazil      BRA   Brazil
## 10 mexico      MEX   Mexico
## # ℹ 240 more rows
```

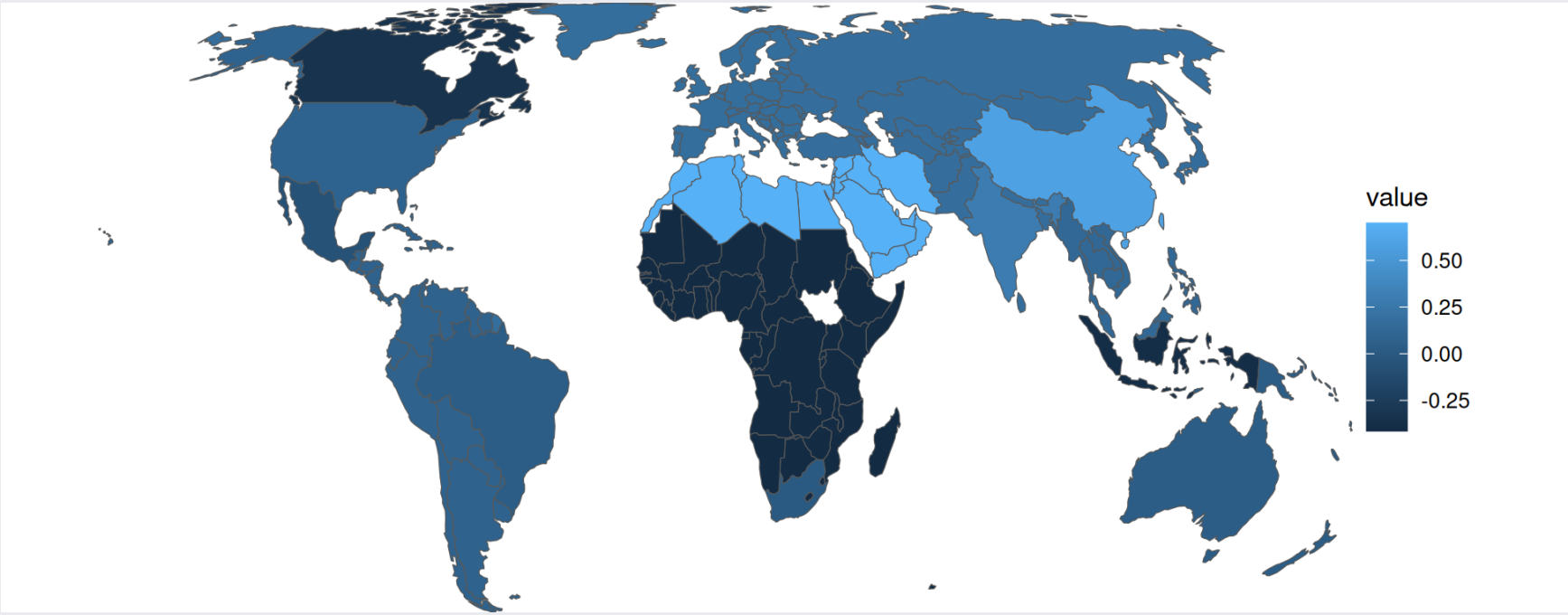
Maps - load world map

```r
library(sf)
library(rnaturalearth)
library(rnaturalearthdata)

world <- ne_countries(scale = "small", returnclass = "sf")
world <- subset(world,!adm0_a3 %in% c("ATA","FJI"))

# merge the WITCH regional definition with the world map
world <- merge(world,wreg, by.x = "adm0_a3", by.y = "ISO")

# merge with the emission data.frame
world0 <- merge(world,qemi |> filter(year == 2100 & e == "co2"), by = "n", allow.cartesian=TRUE)

# Use a better projection 'equal projection'
target_crs <- '+proj=eqearth +wktext'
world1 <- st_transform(world0, crs = target_crs)
```

Ready to plot the map now!

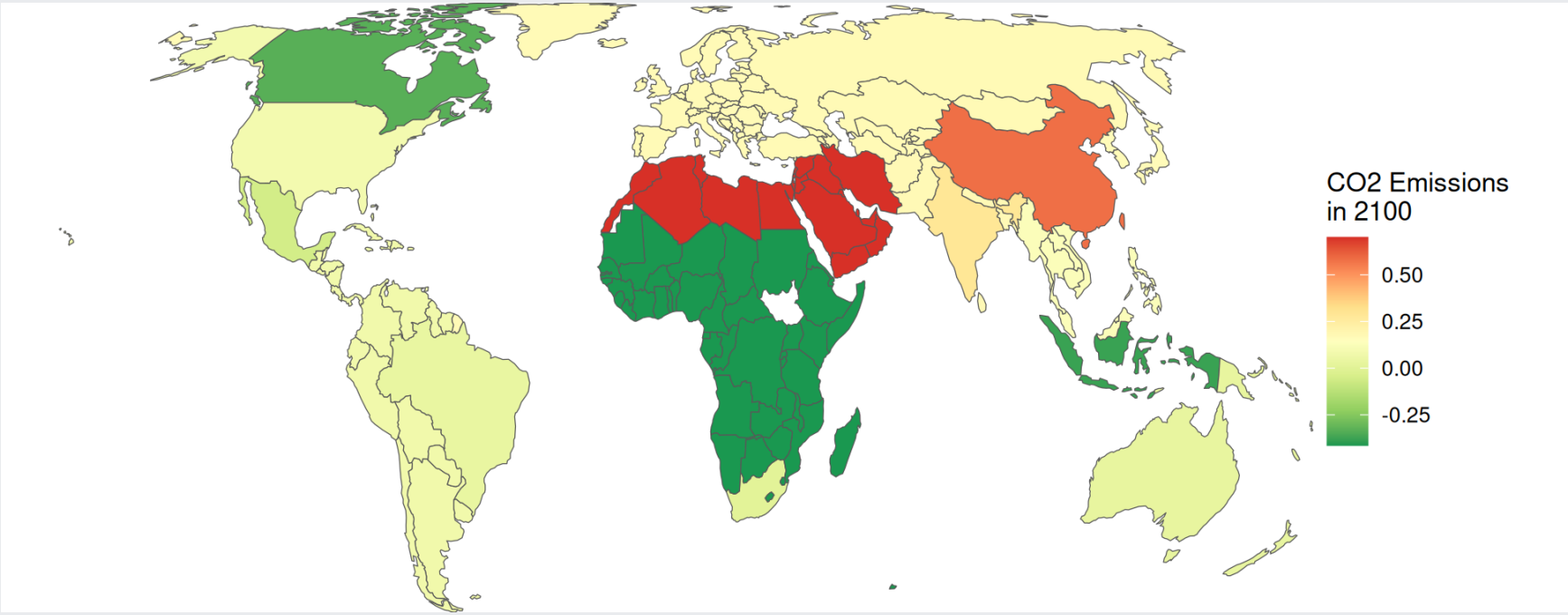
Maps - Showing regional information

```
ggplot(data = world1 ▷ filter(scen == "ctax50")) +
  geom_sf(aes(fill = value)) +
  coord_sf(datum = target_crs, expand = FALSE, clip = "off") +
  theme_void()
```



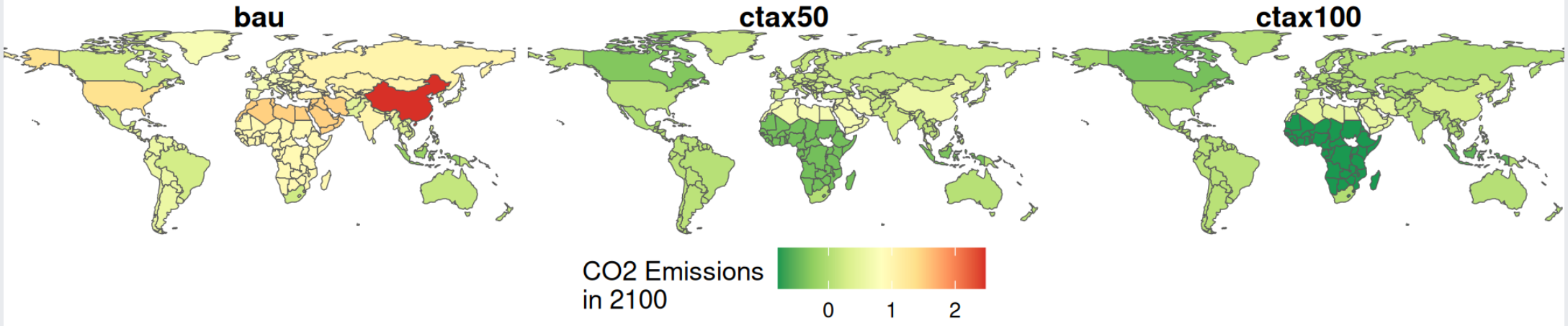
Maps - color palettes are important

```
ggplot(data = world1 ▷ filter(scen == "ctax50")) +
  geom_sf(aes(fill = value)) +
  coord_sf(datum = target_crs, expand = FALSE, clip = "off") +
  scale_fill_distiller(name = "CO2 Emissions\nin 2100", palette ="RdYlGn", direction=-1) +
  theme_void()
```



Maps - Facets are also possible

```
ggplot(data = world0) +
  geom_sf(aes(fill = value)) +
  coord_sf(datum = target_crs, expand = FALSE, clip = "off") +
  scale_fill_distiller(name = "CO2 Emissions\nin 2100", palette ="RdYlGn", direction=-1) +
  theme_void() +
  theme(legend.position = "bottom",
        strip.text.x = element_text(size = 12, face="bold"))+
  facet_grid(~scen)
```

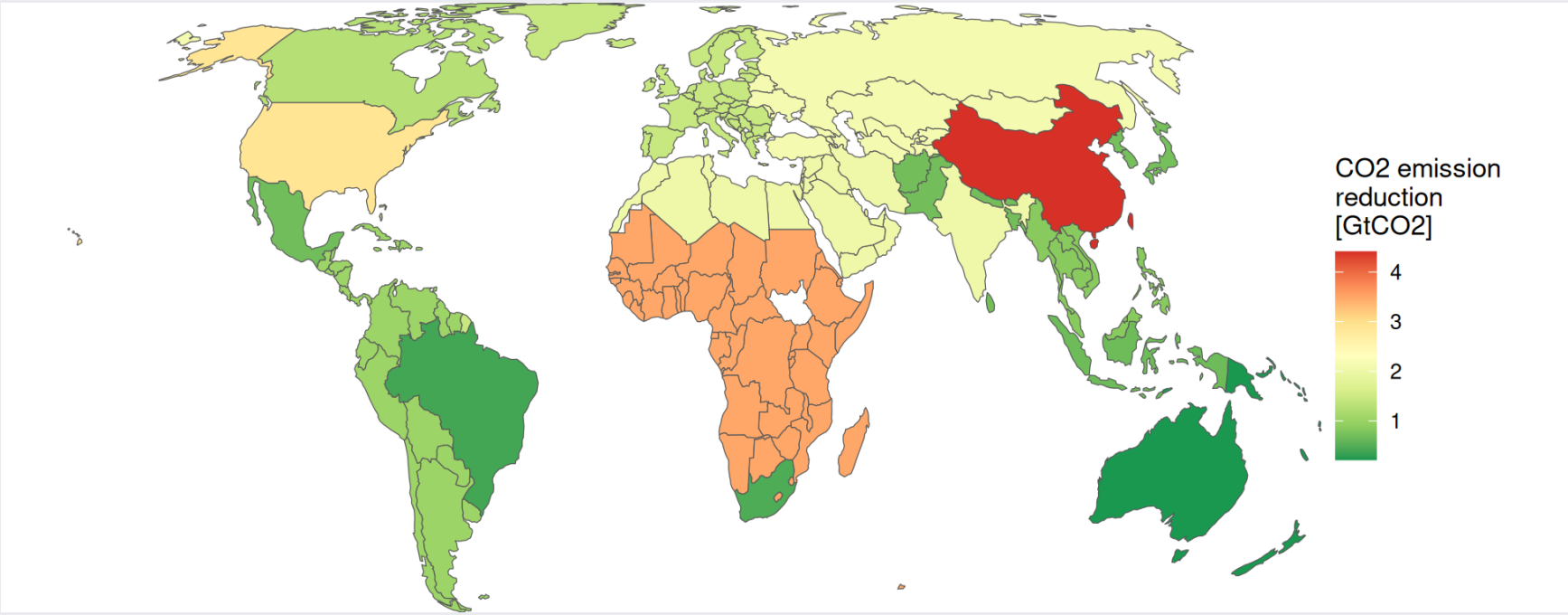


Transforming variables for deeper analysis

```r
# Put the scenarios values in columns
dqemi <- qemi |>
  select(-t,-gdx) |>
  filter(e == "co2" & year == 2100) |>
  pivot_wider(names_from = "scen", values_from = "value")

# Let's create a new variable/column
dqemi <- dqemi |> mutate(dif_wrtBAU = bau - ctax100)

# merge with the emission data.frame
world2 <- merge(world,dqemi, by = "n", allow.cartesian=TRUE)

# Use a better projection 'equal projection'
target_crs <- '+proj=eqearth +wktext'
world3 <- st_transform(world2, crs = target_crs)
```

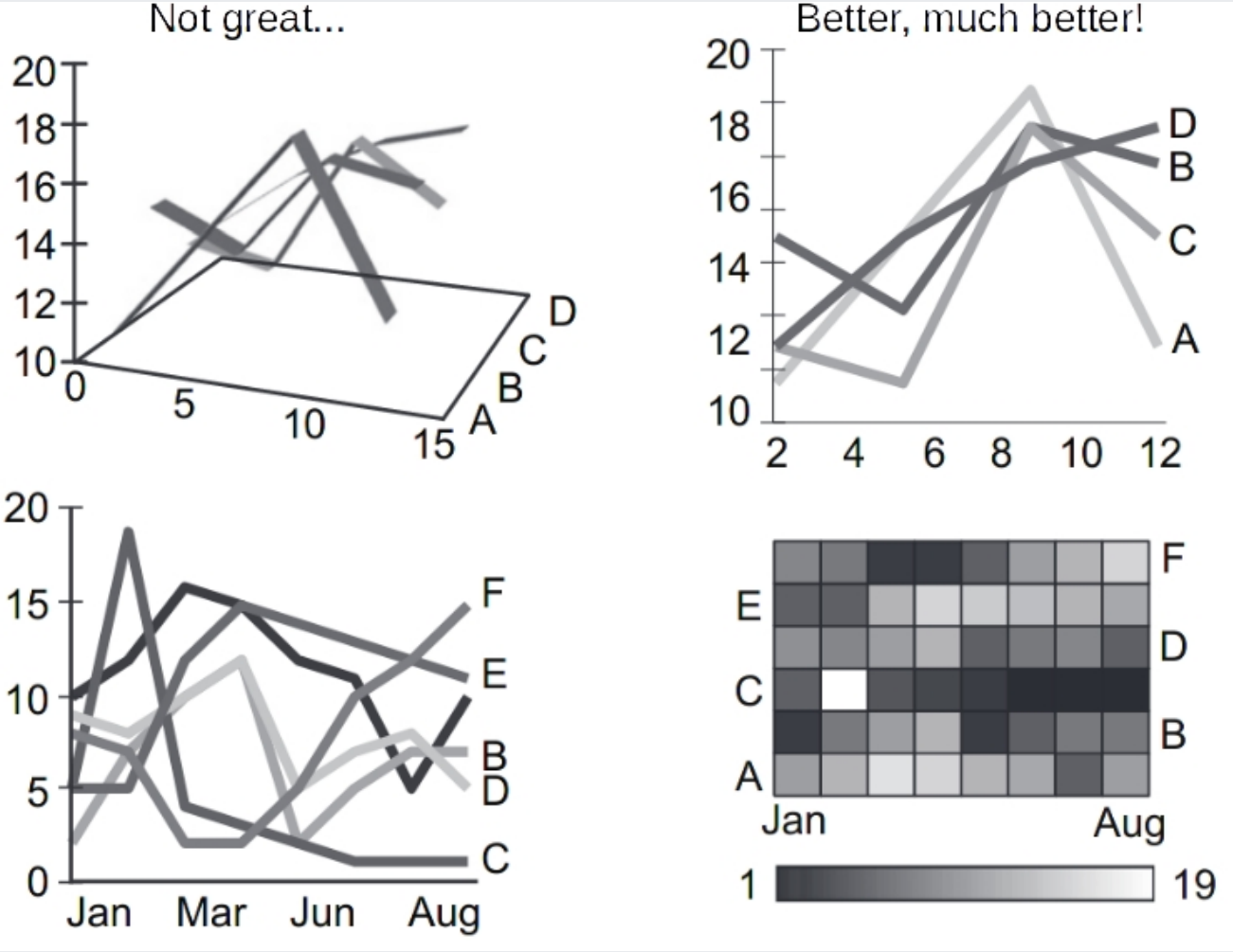
Transforming variables

```
ggplot(data = world3) +
  geom_sf(aes(fill = dif_wrtBAU * 44 / 22)) +
  coord_sf(datum = target_crs, expand = FALSE, clip = "off") +
  scale_fill_distiller(name = "CO2 emission\nreduction\n[GtCO2]",
                       palette ="RdYlGn", direction = -1) +
  theme_void()
```



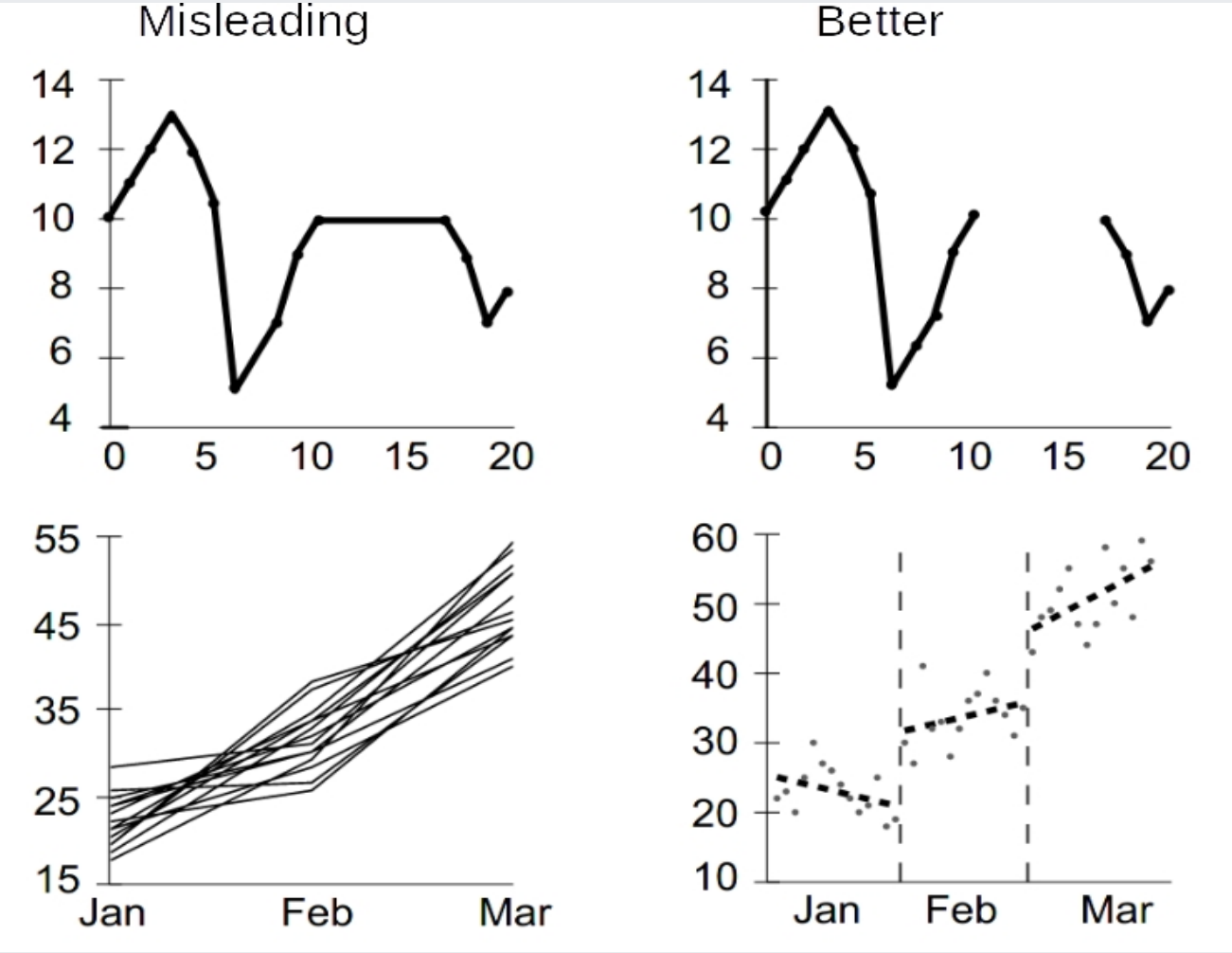
Tips for good visualization

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

- RStudio Cheatsheets https://www.rstudio.com/resources/cheatsheets/

ggplot2

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

Questions

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