Global irrigation water demands biased by unreliable irrigation efficiencies

R code

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Contents

1 Preliminary steps

```r
# Function to read in all required packages in one go:
loadPackages <- function(x) {
  for(i in x) {
    if(!require(i, character.only = TRUE)) {
      install.packages(i, dependencies = TRUE)
      library(i, character.only = TRUE)
    }
  }
}

# Load the packages
loadPackages(c("data.table", "tidyverse", "sensobol", "wesanderson",
               "cowplot", "parallel", "foreach", "doParallel",
               "countrycode", "ggridges", "scales", "overlapping",
               "sp", "rworldmap", "ncdf4", "benchmarkme"))

# Create custom theme
theme_AP <- function() {
  theme_bw() +
    theme(panel.grid.major = element_blank(),
          panel.grid.minor = element_blank(),
          legend.background = element_rect(fill = "transparent",
                                           color = NA),
          legend.key = element_rect(fill = "transparent",
                                    color = NA),
          legend.position = "top",
          strip.background = element_rect(fill = "white"),
          plot.margin = margin(t = 0, r = 0.3, b = 0, l = 0.3, unit ="cm"))
}

# Set checkpoint

dir.create(".checkpoint")
library("checkpoint")

checkpoint("2021-08-02",
           R.version ="4.0.3",
           checkpointLocation = getwd())
```

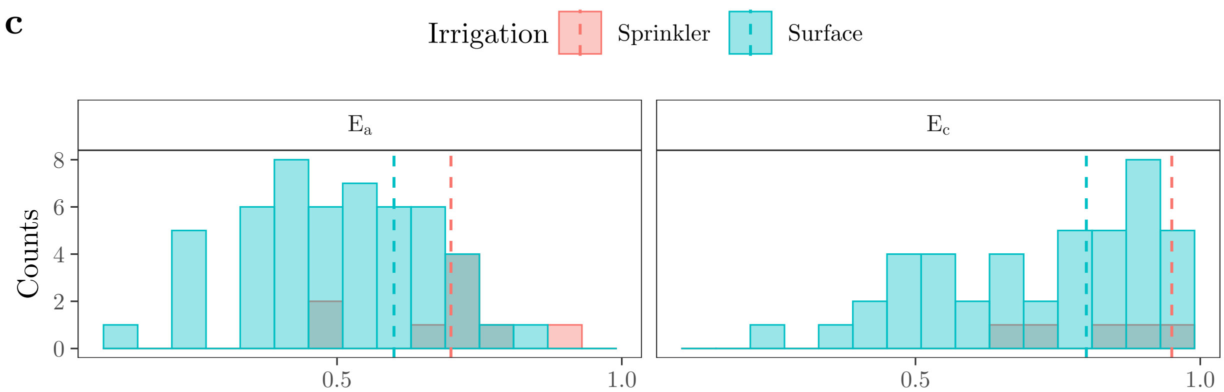
2 Read in data

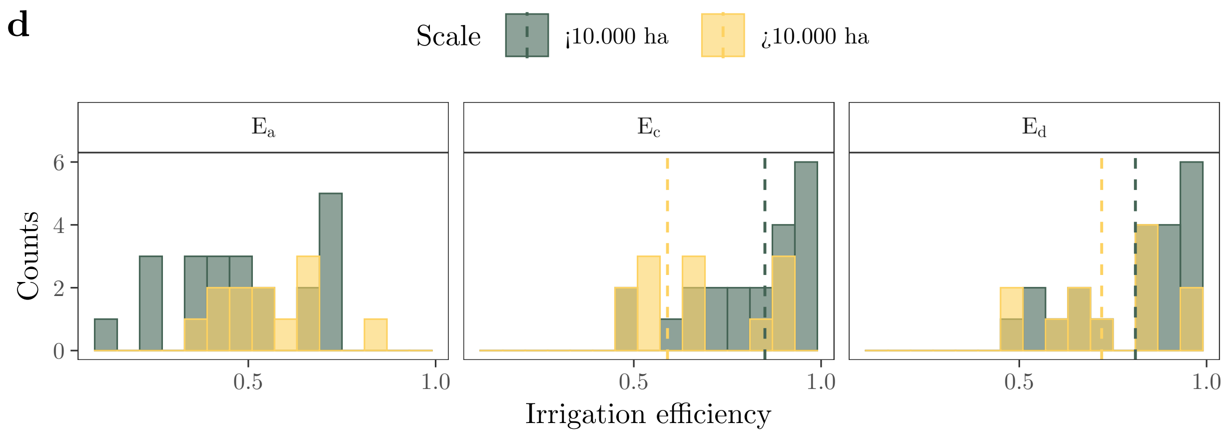
```r
# READ IN DATA ---------------------------------------------------------------------

# Rohwer data
rohwer <- fread("rohwer_data_all.csv")
rohwer[rohwer == ""] <- NA
rohwer <- rohwer[, Large_fraction:= Large_fraction / 100]

# Jager data
jager <- fread("jager_data.csv")
jager.list <- split(jager, jager$Country)

# Bos data
bos <- fread("bos_data.csv")
bos <- bos[, Scale := ifelse(Irrigated_area < 10000, "<10.000 ha", ">10.000 ha")]

# Solley data (USA)
usa.dt <- fread("usa_efficiency.csv")
usa.dt <- usa.dt[, Efficiency:= consumptive.use / total.withdrawal]

# FAO 1997 data (Irrigation potential in Africa)
fao_dt <- fread("fao_1997.csv")
fao_dt <- fao_dt[, Efficiency:= Efficiency / 100]

# Create data set with E_a values as defined by Rohwer
bos.rohwer.ea <- data.table("Irrigation" = c("Surface", "Sprinkler"),
                            "Value" = c(0.6, 0.7),
                            "variable" = "E[a]")

# Create data set with E_c values as defined by Rohwer
bos.rohwer.ec <- data.table("Irrigation" = c("Surface", "Sprinkler"),
                            "Value" = c(0.8, 0.95),
                            "variable" = "E[c]")

bos.rohwer.all <- rbind(bos.rohwer.ec, bos.rohwer.ea)

# As a function of scale
bos.rohwer.mf.ec <- data.table("Scale" = c("<10.000 ha", ">10.000 ha"),
                               "Value" = c(0.85, 0.59),
                               "variable" = "E[c]")

bos.rohwer.mf.ed <- data.table("Scale" = c("<10.000 ha", ">10.000 ha"),
                               "Value" = c(0.81, 0.72),
                               "variable" = "E[d]")

bos.rohwer.mf.all <- rbind(bos.rohwer.mf.ec, bos.rohwer.mf.ed)
```

```r
# PLOT -------------------------------------------------------------------------------------

bos2 <- copy(bos)
bos2 <- setnames(bos2, c("E_a", "E_c", "E_d"), c("E[a]", "E[c]", "E[d]"))

# Field and conveyance efficiency ----------------

a <- bos2 %>%
  melt(., measure.vars = c("E[a]", "E[c]")) %>%
  ggplot(., aes(value, fill = Irrigation, color = Irrigation)) +
  geom_histogram(position = "identity", alpha = 0.4, bins = 15) +
  facet_wrap(~variable, labeller = label_parsed) +
  scale_x_continuous(breaks = pretty_breaks(n = 3)) +
  geom_vline(data = bos.rohwer.all, aes(xintercept = Value,
                                        color = Irrigation,
                                        group = variable),
             lty = 2,
             size = 1) +
  labs(x = "", y = "Counts") +
  theme_AP()

# As a function of scale ----------------------

b <- melt(bos2, measure.vars = c("E[c]", "E[a]", "E[d]")) %>%
  na.omit() %>%
  ggplot(., aes(value, fill = Scale, color = Scale)) +
  geom_histogram(bins = 15, position = "identity", alpha = 0.6) +
  labs(x = "Irrigation efficiency", y = "Counts") +
  facet_wrap(~ variable, labeller = label_parsed) +
  geom_vline(data = bos.rohwer.mf.all, aes(xintercept = Value,
                                          color = Scale,
                                          group = variable),
             lty = 2,
             size = 1) +
  scale_x_continuous(breaks = pretty_breaks(n = 3)) +
  scale_color_manual(values = wes_palette(2, name = "Chevalier1"),
                     name = "Scale",
                     labels = c("<10.000 ha", ">10.000 ha")) +
  scale_fill_manual(values = wes_palette(2, name = "Chevalier1"),
                    name = "Scale",
                    labels = c("<10.000 ha", ">10.000 ha")) +
  theme_AP()

bottom <- plot_grid(a, b, ncol = 1, labels = c("c", "d"))
```

```
## Warning: Removed 74 rows containing non-finite values (stat_bin).
```

```
bottom
```

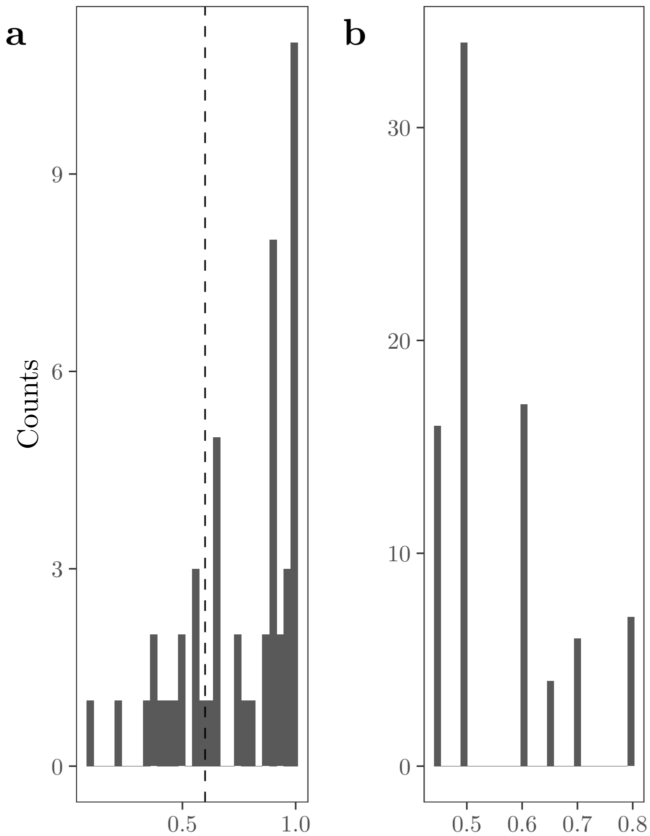




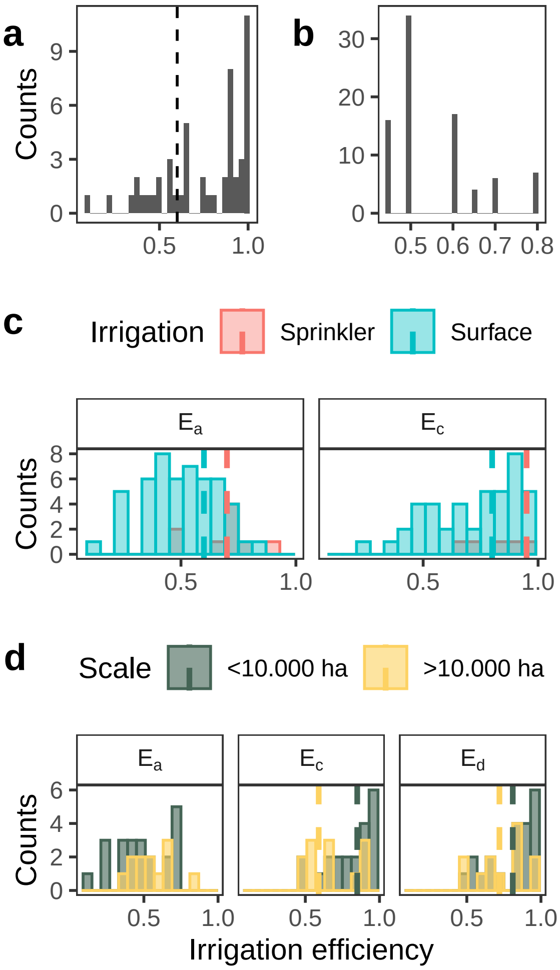

```
# PLOT USA AND AFRICA -----------------------------------------------------------

c1 <- ggplot(usa.dt, aes(Efficiency)) +
  geom_histogram() +
  scale_x_continuous(breaks = pretty_breaks(n = 3)) +
  geom_vline(xintercept = 0.6, lty = 2) +
  labs(x = "", y = "Counts") +
  theme_AP()

d1 <- ggplot(fao_dt, aes(Efficiency)) +
  geom_histogram() +
  scale_x_continuous(breaks = pretty_breaks(n = 3)) +
  labs(x = "", y = "") +
  theme_AP()

top <- cowplot::plot_grid(c1, d1, ncol = 2, labels = "auto")
```

```
## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

## Warning: Removed 3 rows containing non-finite values (stat_bin).

## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.
```

```r
top
```




```r
# PLOT MERGED -----------------------------------------------------------------

plot_grid(top, bottom, ncol = 1, rel_heights = c(0.3, 0.7))
```



3 The model

3.1 Function to create sample matrix

```
# CREATE FUNCTION TO DESIGN SAMPLE MATRIX ------------------------------------------

params_algo <- list(
  "Surface" = c("Ea_surf", "Ec_surf", "m", "r_L", "X1", "X2"),
  "Sprinkler" = c("Ea_sprinkler", "Ec_sprinkler", "m"),
  "Micro" = c("Ea_micro", "Ec_micro", "m"),
  "Mixed" = c("Ea_surf", "Ea_sprinkler", "Ec_surf", "Ec_sprinkler", "m", "r_L", "X1", "X2"),
  "Jager" = c("Ea_surf", "Ea_sprinkler", "Ec_surf", "Ec_sprinkler",
              "Ea_micro", "Ec_micro", "m", "r_L", "X1", "X2")
)

params_fun <- function(IFT) {
  out <- params_algo[[IFT]]
  return(out)
}
```

```r
sample_matrix_fun <- function(IFT) {
  params <- params_fun(IFT = IFT)
  mat <- sensobol::sobol_matrices(N = N, params = params)
  out <- list(params, mat)
  names(out) <- c("parameters", "matrix")
  return(out)
}
```

3.2 Define distributions

```r
# DEFINE TRUNCATED DISTRIBUTIONS -------------------------------------------------

# EA SURFACE ---------

Ea.surface <- bos[Irrigation == "Surface"][, .(min = min(E_a, na.rm = TRUE),
                                              max = max(E_a, na.rm = TRUE))]
shape <- 3.502469
scale <- 0.5444373
minimum <- Ea.surface$min
maximum <- Ea.surface$max
weibull_dist <- sapply(c(minimum, maximum), function(x)
  pweibull(x, shape = shape, scale = scale))

# EC SURFACE --------

Ec.surface <- bos[Irrigation == "Surface"][, .(min = min(E_c, na.rm = TRUE),
                                              max = max(E_c, na.rm = TRUE))]
shape1 <- 5.759496
shape2 <- 1.403552
minimum.beta <- Ec.surface$min
maximum.beta <- Ec.surface$max
beta_dist <- sapply(c(minimum.beta, maximum.beta), function(x)
  pbeta(x, shape1 = shape1, shape2 = shape2))

# EA SPRINKLER --------

Ea.sprinkler <- bos[Irrigation == "Sprinkler"][, .(min = min(E_a, na.rm = TRUE),
                                              max = max(E_a, na.rm = TRUE))]
shape.spr <- 6.9913711
scale.spr <- 0.7451178
minimum.spr <- Ea.sprinkler$min
maximum.spr <- Ea.sprinkler$max
weibull_dist_spr <- sapply(c(minimum.spr, maximum.spr), function(x)
  pweibull(x, shape = shape.spr, scale = scale.spr))

# MANAGEMENT FACTOR (m) -----
```

```r
shape1.m <- 5.759496
shape2.m <- 1.403552
minimum.m <- 0.65
maximum.m <- 1
beta_dist.m <- sapply(c(minimum.m, maximum.m), function(x)
  pbeta(x, shape1 = shape1.m, shape2 = shape2.m))
```

```r
# FUNCTION TO TRANSFORM TO APPROPRIATE DISTRIBUTIONS -------------------------------

distributions_fun <- list(

  # SURFACE IRRIGATION
  # ---------------------------

  "Ea_surf" = function(x) {

    out <- qunif(x, weibull_dist[[1]], weibull_dist[[2]])
    out <- qweibull(out, shape, scale)
  },

  "Ec_surf" = function(x)  {

    out <- qunif(x, beta_dist[[1]], beta_dist[[2]])
    out <- qbeta(out, shape1, shape2)
  },

  # SPRINKLER IRRIGATION
  # --------------------------

  "Ea_sprinkler" = function(x) {

    out <- qunif(x, weibull_dist_spr[[1]], weibull_dist_spr[[2]])
    out <- qweibull(out, shape.spr, scale.spr)
  },

  "Ec_sprinkler" = function(x) qunif(x, 0.64, 0.96),

  # MICRO (DRIP) IRRIGATION
  # --------------------------

  "Ea_micro" = function(x) out <- qunif(x, 0.75, 0.95),
  "Ec_micro" = function(x) out <- qunif(x, 0.9, 0.95),

  # PROPORTION LARGE
  # -------------------------
  "Proportion_large" = function(x) x,
```

```r
  # MANAGEMENT FACTOR
  # -------------------------

  "m" = function(x) {
    out <- qunif(x, beta_dist.m[[1]], beta_dist.m[[2]])
    out <- qbeta(out, shape1.m, shape2.m)
    },

  # REDUCTION IN MANAGEMENT FACTOR DUE TO LARGE-SCALE
  # ---------------------------
  "r_L" = function(x) qunif(x, 0, 0.5),

  # IRRIGATED AREA DATASET
  # ---------------------------

  "X1" = function(x) floor(x * (4 - 1 + 1)) + 1,

  # THRESHOLD FOR LARGE-SCALE IRRIGATED AREAS
  # ----------------------------

  "X2" = function(x) floor(x * (5 - 1 + 1)) + 1
)
```

3.3 Uncertainty in the proportion of large-scale irrigated areas

```r
# DEFINE THE UNCERTAINTY IN THE LARGE FRACTION AT THE COUNTRY LEVEL ----------------

rohwer.frac <- rohwer[, .(Country, Large_fraction)]
rohwer.frac[, `:=` (min = Large_fraction, max = Large_fraction + 0.1)]

countries.list <- split(rohwer.frac, seq(nrow(rohwer.frac)))
names(countries.list) <- rohwer$Country

n.rows <- nrow(rohwer)
triggers.dt <- rohwer[rep(seq_len(n.rows), 4 * 5)][, .(Country, IFT)] %>%
  .[, X1:= rep(1:4, each = n.rows, times = 5)] %>%
  .[, X2:= rep(1:5, each = n.rows, times = 4)] %>%
  .[, Proportion_large:= runif(n.rows * 4 * 5, min = 0.01, max = 0.7)] %>%
  .[, index:= paste(Country, X1, X2, sep = ".")]

triggers.dt <- setkey(triggers.dt, index)
```

3.4 Function to create sample matrix and transfrom to appropriate distributions

```r
# FULL ALGORITHM TO CREATE SAMPLE MATRIX ------------------------------------------
```

```r
full_sample_matrix <- function(IFT, Country) {
  tmp <- sample_matrix_fun(IFT = IFT)
  mat <- tmp[["matrix"]]
  temp <- colnames(mat)
  mat <- sapply(seq_along(temp), function(x) distributions_fun[[temp[x]]](mat[, x]))
  colnames(mat) <- temp
  countries.frac <- countries.list[[Country]]
  out <- list(tmp$parameters, mat)
  names(out) <- c("parameters", "matrix")
  return(out)
}
```

3.5 Define the model

```r
# FULL MODEL ----------------------------------------------------------------------

full_model <- function(IFT, Country, sample.size, R) {

  country.differences <- setdiff(rohwer$Country, jager$Country)
  tmp <- full_sample_matrix(IFT = IFT, Country = Country)
  mat <- tmp$matrix

  if(IFT == "Surface" | IFT == "Mixed" | IFT == "Jager") {
    X1 <- mat[, "X1"]
    X2 <- mat[, "X2"]
    index <- paste(Country, X1, X2, sep = ".")
    Proportion_large <- triggers.dt[index][, Proportion_large]
  }

  if(IFT == "Surface") {

    Mf <- mat[, "m"] - mat[, "r_L"] * Proportion_large
    y <- mat[, "Ea_surf"] * mat[, "Ec_surf"] * Mf

  } else if(IFT == "Sprinkler") {

    Mf <- mat[, "m"]
    y <- mat[, "Ea_sprinkler"] * mat[, "Ec_sprinkler"] * Mf

  } else if(IFT == "Mixed") {

    Mf.surf <- mat[, "m"] - mat[, "r_L"] * Proportion_large
    y.surf <- mat[, "Ea_surf"] * mat[, "Ec_surf"] * Mf.surf

    Mf.sprink <- mat[, "m"]
    y.sprink <- mat[, "Ea_sprinkler"] * mat[, "Ec_sprinkler"] * Mf.sprink
```

```
    y <- 0.5 * y.surf + 0.5 * y.sprink

  } else if(IFT == "Micro") {

    Mf <- mat[, "m"]
    y <- mat[, "Ea_micro"] * mat[, "Ec_micro"] * Mf

  } else if(IFT == "Jager") {

    if(Country %in% country.differences == TRUE) {
      next
    }

    Mf.surf <- mat[, "m"] - mat[, "r_L"] * Proportion_large
    y.surf <- mat[, "Ea_surf"] * mat[, "Ec_surf"] * Mf.surf

    Mf.spr <- mat[, "m"]
    y.spr <- mat[, "Ea_sprinkler"] * mat[, "Ec_sprinkler"] * Mf.spr

    Mf.micro <- mat[, "m"]
    y.micro <- mat[, "Ea_micro"] * mat[, "Ec_micro"] * Mf.micro

    y <- jager.list[[Country]]$Surface_fraction * y.surf +
      jager.list[[Country]]$Sprinkler_fraction * y.spr +
      jager.list[[Country]]$Drip_fraction * y.micro

  }

  ind <- sobol_indices(N = sample.size, Y = y, params = tmp$parameters,
                       boot = TRUE, R = R)
  out <- list(y, ind)
  names(out) <- c("output", "indices")
  return(out)
}
```

3.6 Define settings

```
# DEFINE SETTINGS -----------------------------------------------------------------

N <- 2^14
R <- 10^2
list_continents <- list(c("Africa", "Asia"), c("Americas", "Europe"))
```

3.7 Run the model in parallel

```
# RUN MODEL ----------------------------------------------------------------------
```

```r
new.rohwer <- rohwer[Country %in% jager$Country][, IFT:= "Jager"]
all.dt <- list(rohwer, new.rohwer)

y <- list()
for(j in 1:length(all.dt)) {
  y[[j]] <- mclapply(1:nrow(all.dt[[j]]), function(x)
    full_model(IFT = all.dt[[j]][[x, "IFT"]],
               Country = all.dt[[j]][[x, "Country"]],
               sample.size = N,
               R = R),
    mc.cores = detectCores() * 0.75)
}
```

3.8 Extract model output

```r
# EXTRACT MODEL OUTPUT -----------------------------------------------------------

names(y) <- c("Rohwer et al. 2007", "Jägermeyr et al. 2015")

output <- tmp <- list()
for(i in names(y)) {
  output[[i]] <- lapply(y[[i]], function(x) x[["output"]][1:(2 * N)])

  if(i == "Rohwer et al. 2007") {

    names(output[[i]]) <- rohwer$Country

  } else if(i == "Jägermeyr et al. 2015") {

    names(output[[i]]) <- new.rohwer$Country

  }
  tmp[[i]] <- lapply(output[[i]], data.table) %>%
    rbindlist(., idcol = "Country")

  if(i == "Rohwer et al. 2007") {

    tmp[[i]] <- merge(tmp[[i]], rohwer[, .(Country, IFT)], all.x = TRUE) %>%
      .[, IFT:= factor(IFT, levels = c("Surface", "Sprinkler", "Micro", "Mixed"))]

  } else if(i == "Jägermeyr et al. 2015") {

    tmp[[i]] <- tmp[[i]][, IFT:= "Jager"]

  }

  tmp[[i]] <- tmp[[i]][, Continent:= countrycode(tmp[[i]][, Country],
```

```
                                                origin = "country.name",
                                                destination = "continent")]
}
```

```
## Warning in countrycode_convert(sourcevar = sourcevar, origin = origin, destination = dest,

## Warning in countrycode_convert(sourcevar = sourcevar, origin = origin, destination = dest,
```

```
uncertainty.dt <- rbindlist(tmp, idcol = "Approach")
uncertainty.dt <- uncertainty.dt[, Study:= ifelse(IFT == "Jager",
                                                 "Jägermeyr et al. approach",
                                                 "Rohwer et al. approach")]
```

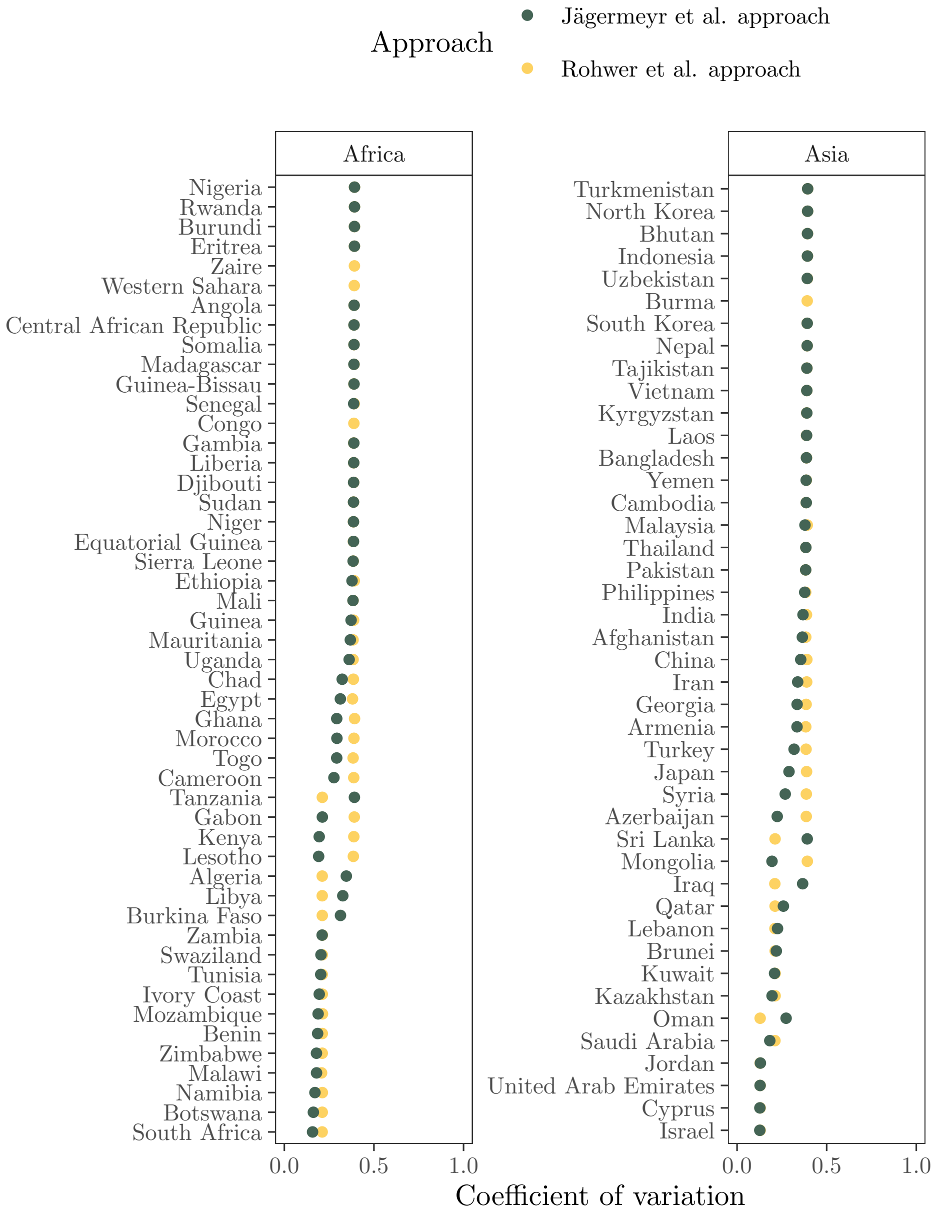
```
# EXPORT UNCERTAINTY IN IRRIGATION EFFICIENCY ------------------------------------

fwrite(uncertainty.dt, "uncertainty.dt.csv")
```

4 Uncertainty analysis

4.1 Coefficient of variation

```
# CALCULATE COEFFICIENT OF VARIATION ---------------------------------------------

cv.dt <- uncertainty.dt[, .(sd = sd(V1), mean = mean(V1)),
                        .(Country, Approach, Continent)] %>%
  .[, cv:= sd / mean]

dd <- list()
for (i in 1:length(list_continents)) {
  dd[[i]] <- ggplot(cv.dt[Continent %in% list_continents[[i]]],
                    aes(reorder(Country, cv), cv, color = Approach)) +
    geom_point() +
    scale_color_manual(values = wes_palette("Chevalier1"),
                       labels = c("Jägermeyr et al. approach",
                                  "Rohwer et al. approach")) +
    labs(y = "Coefficient of variation",
         x = "") +
    facet_wrap(~Continent, scales = "free_y") +
    scale_y_continuous(limits = c(0, 1),
                       breaks = pretty_breaks(n = 3)) +

    coord_flip() +
    theme_AP() +
    guides(color = guide_legend(nrow = 2, byrow = TRUE))
}

dd
```

[[1]]



Approach
Jägermeyr et al. approach
Rohwer et al. approach
Africa
Asia
Nigeria
Rwanda
Burundi
Eritrea
Zaire
Western Sahara
Angola
Central African Republic
Somalia
Madagascar
Guinea-Bissau
Senegal
Congo
Gambia
Liberia
Djibouti
Sudan
Niger
Equatorial Guinea
Sierra Leone
Ethiopia
Mali
Guinea
Mauritania
Uganda
Chad
Egypt
Ghana
Morocco
Togo
Cameroon
Tanzania
Gabon
Kenya
Lesotho
Algeria
Libya
Burkina Faso
Zambia
Swaziland
Tunisia
Ivory Coast
Mozambique
Benin
Zimbabwe
Malawi
Namibia
Botswana
South Africa
Turkmenistan
North Korea
Bhutan
Indonesia
Uzbekistan
Burma
South Korea
Nepal
Tajikistan
Vietnam
Kyrgyzstan
Laos
Bangladesh
Yemen
Cambodia
Malaysia
Thailand
Pakistan
Philippines
India
Afghanistan
China
Iran
Georgia
Armenia
Turkey
Japan
Syria
Azerbaijan
Sri Lanka
Mongolia
Iraq
Qatar
Lebanon
Brunei
Kuwait
Kazakhstan
Oman
Saudi Arabia
Jordan
United Arab Emirates
Cyprus
Israel
0.0
0.5
1.0
Coefficient of variation

##
[[2]]

4.2 Ranges

```
# COMPUTE RANGES -----------------------------------------------------------------

calc <- uncertainty.dt[, .(min = min(V1), max = max(V1)), .(Continent, Country)] %>%
  .[, .(range = max - min), .(Continent, Country)] %>%
  .[order(range)]

print(calc, n = Inf)
```

```
##      Continent                   Country     range
##   1:      Asia                    Cyprus 0.4641096
##   2:      Asia      United Arab Emirates 0.4866356
```

```
##  3:     Asia                          Israel 0.4944147
##  4:     Asia                          Jordan 0.5057459
##  5:   Europe                     Netherlands 0.5673924
##  6: Americas                            Cuba 0.5755095
##  7:   Africa                         Tunisia 0.5764236
##  8:   Africa                      Mozambique 0.5767331
##  9:   Africa                        Zimbabwe 0.5783439
## 10:   Africa                           Benin 0.5789929
## 11:   Europe                           Italy 0.5801489
## 12:   Europe                          France 0.5804556
## 13:   Africa                         Namibia 0.5822584
## 14: Americas                   United States 0.5834569
## 15:     Asia                          Brunei 0.5857038
## 16:     Asia                         Lebanon 0.5861990
## 17:     Asia                      Kazakhstan 0.5879825
## 18:     Asia                    Saudi Arabia 0.5884782
## 19:   Africa                          Zambia 0.5902938
## 20:   Africa                    South Africa 0.5905044
## 21: Americas                          Brazil 0.5919833
## 22:   Africa                       Swaziland 0.5921023
## 23:   Africa                     Ivory Coast 0.5939957
## 24:   Europe                         Austria 0.6014893
## 25:   Europe                         Belgium 0.6014893
## 26:     <NA>                        Byelarus 0.6014893
## 27:   Europe                         Denmark 0.6014893
## 28:   Europe                         Finland 0.6014893
## 29:   Europe                         Germany 0.6014893
## 30:   Europe                          Greece 0.6014893
## 31:   Europe                         Hungary 0.6014893
## 32:   Europe                          Latvia 0.6014893
## 33:   Europe                       Lithuania 0.6014893
## 34:   Europe                      Luxembourg 0.6014893
## 35:   Africa                          Malawi 0.6014893
## 36:   Europe                        Slovakia 0.6014893
## 37:   Europe                          Sweden 0.6014893
## 38:   Europe                     Switzerland 0.6014893
## 39:     Asia                          Kuwait 0.6016086
## 40:   Europe                           Spain 0.6044159
## 41: Americas                          Canada 0.6058219
## 42:   Africa                        Botswana 0.6076223
## 43:   Europe                         Ukraine 0.6139551
## 44:     Asia                           Qatar 0.6206659
## 45:   Europe                          Russia 0.6462099
## 46:   Europe                  Czech Republic 0.6472857
## 47:   Europe                  United Kingdom 0.6534832
## 48:   Europe                         Romania 0.6568256
## 49:   Europe                         Croatia 0.6582100
## 50:   Europe                        Slovenia 0.6631916
```

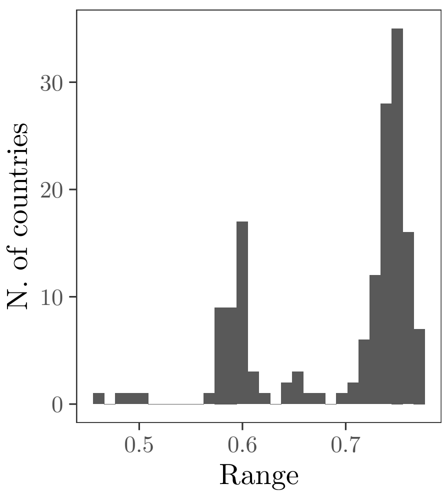
```
## 51:   Africa             Burkina Faso 0.6718699
## 52:   Africa                    Libya 0.6973910
## 53:   Europe                  Moldova 0.7086949
## 54:   Africa                  Algeria 0.7088434
## 55:   Africa                     Chad 0.7142740
## 56:     Asia                    Syria 0.7157040
## 57:   Europe                   Serbia 0.7175545
## 58:  Oceania         Papua New Guinea 0.7186161
## 59:   Europe                 Bulgaria 0.7186650
## 60: Americas                  Jamaica 0.7218540
## 61: Americas                   Mexico 0.7248560
## 62:  Oceania                Australia 0.7267790
## 63:   Europe   Bosnia and Herzegovina 0.7277615
## 64:     Asia                  Armenia 0.7278218
## 65:   Africa                  Morocco 0.7291735
## 66:   Africa                    Ghana 0.7305429
## 67:   Africa           Western Sahara 0.7323095
## 68: Americas                Argentina 0.7323171
## 69: Americas                 Colombia 0.7324198
## 70: Americas                Venezuela 0.7328742
## 71:     Asia                     Iran 0.7330428
## 72:     Asia               Azerbaijan 0.7333914
## 73:     Asia                    China 0.7341298
## 74: Americas                  Ecuador 0.7343571
## 75: Americas              El Salvador 0.7345590
## 76:   Africa                    Gabon 0.7353623
## 77:     Asia                    India 0.7353925
## 78: Americas              Puerto Rico 0.7357588
## 79: Americas               Costa Rica 0.7360408
## 80: Americas                    Chile 0.7365217
## 81:   Africa               Mauritania 0.7367003
## 82: Americas                   Panama 0.7368114
## 83: Americas                  Bolivia 0.7370244
## 84: Americas                 Suriname 0.7387122
## 85: Americas            French Guiana 0.7387628
## 86:   Africa                 Cameroon 0.7388522
## 87:     Asia                     Iraq 0.7389065
## 88:  Oceania              New Zealand 0.7389989
## 89:   Europe                   Poland 0.7393614
## 90: Americas                 Paraguay 0.7398433
## 91:   Africa                   Guinea 0.7400750
## 92:   Africa                  Lesotho 0.7401646
## 93:     Asia                   Turkey 0.7402977
## 94:   Africa                   Uganda 0.7407207
## 95:     Asia                 Malaysia 0.7413572
## 96:   Africa                    Kenya 0.7416232
## 97: Americas                  Uruguay 0.7426133
## 98:   Africa                    Zaire 0.7427597
```

```
## 99:    Africa                   Nigeria 0.7428266
## 100:      Asia                Tajikistan 0.7439456
## 101:    Africa                  Djibouti 0.7447347
## 102:      Asia               Afghanistan 0.7453029
## 103:    Africa                  Ethiopia 0.7453914
## 104:      Asia                  Mongolia 0.7458044
## 105:      Asia                 Sri Lanka 0.7460123
## 106:    Africa                   Senegal 0.7460561
## 107:    Africa                     Egypt 0.7465109
## 108:  Americas                      Peru 0.7465975
## 109:    Africa                     Congo 0.7477196
## 110:    Africa                      Mali 0.7481701
## 111:      Asia                   Georgia 0.7484232
## 112:      Asia                     Japan 0.7485508
## 113:      Asia                   Vietnam 0.7488066
## 114:  Americas        Dominican Republic 0.7490021
## 115:    Africa                    Angola 0.7494520
## 116:    Africa                   Somalia 0.7498927
## 117:      Asia                  Thailand 0.7500141
## 118:    Africa                     Niger 0.7501017
## 119:    Africa                   Eritrea 0.7506740
## 120:  Americas                    Guyana 0.7511102
## 121:      Asia               South Korea 0.7513679
## 122:      Asia                Uzbekistan 0.7515984
## 123:  Americas                 Guatemala 0.7522521
## 124:      Asia                 Indonesia 0.7523546
## 125:      Asia                    Bhutan 0.7524556
## 126:  Americas                 Nicaragua 0.7524794
## 127:      Asia                Bangladesh 0.7526387
## 128:      Asia                     Yemen 0.7533179
## 129:  Americas                    Belize 0.7534902
## 130:    Europe                 Macedonia 0.7538931
## 131:    Africa             Guinea-Bissau 0.7545221
## 132:  Americas                     Haiti 0.7545770
## 133:    Africa                    Rwanda 0.7551263
## 134:    Africa                    Gambia 0.7551399
## 135:      Asia                  Cambodia 0.7552400
## 136:      Asia                Kyrgyzstan 0.7559198
## 137:    Africa                Madagascar 0.7559324
## 138:    Africa         Equatorial Guinea 0.7569197
## 139:      Asia                     Nepal 0.7571390
## 140:      Asia                      Laos 0.7575573
## 141:    Africa                  Tanzania 0.7576033
## 142:    Europe                   Albania 0.7584757
## 143:      Asia              Turkmenistan 0.7591862
## 144:    Africa                     Sudan 0.7594946
## 145:  Americas                  Honduras 0.7600602
## 146:    Africa Central African Republic 0.7600622
```

```
## 147:    Africa                  Liberia 0.7619743
## 148:    Africa             Sierra Leone 0.7631982
## 149:      Asia                    Burma 0.7636254
## 150:    Africa                     Togo 0.7637762
## 151:    Europe                   Norway 0.7643408
## 152:      Asia              North Korea 0.7660183
## 153:    Africa                  Burundi 0.7663720
## 154:    Europe                 Portugal 0.7670973
## 155:  Americas                 Trinidad 0.7678994
## 156:      Asia              Philippines 0.7739224
## 157:      Asia                 Pakistan 0.7744971
## 158:      Asia                     Oman 0.7747888
##      Continent                  Country     range
```

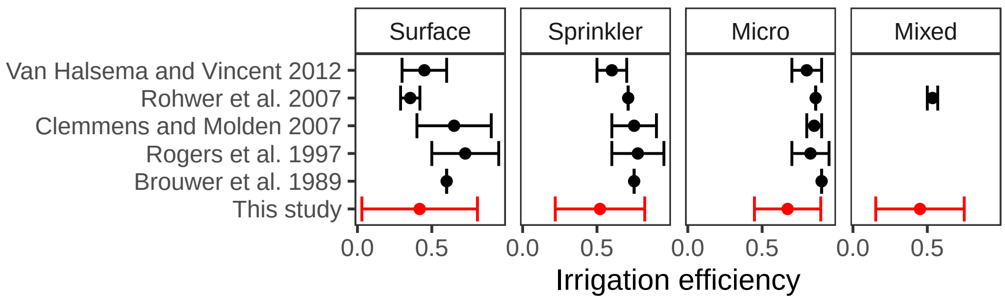
```
ggplot(calc, aes(range)) +
  geom_histogram() +
  labs(x = "Range", y = "N. of countries") +
  theme_AP()
```

```
## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.
```




```
# COMPARE RANGES ---------------------------------------------------------------

ranges_empirical <- uncertainty.dt[, .(higher = max(V1), lower = min(V1)), IFT] %>%
  .[, Study:= "This study"]%>%
  .[!IFT == "Jager"]

ranges_efficiencies <- fread("ranges_efficiencies.csv")

rbind(ranges_empirical, ranges_efficiencies)[, mean.value:= (higher + lower) / 2] %>%
  .[, Study:= factor(Study, levels = c("This study",
                                       "Brouwer et al. 1989",
                                       "Rogers et al. 1997",
                                       "Clemmens and Molden 2007",
                                       "Rohwer et al. 2007",
```

```
                                              "Van Halsema and Vincent 2012"))] %>%
  na.omit() %>%
  ggplot(., aes(mean.value, Study, color = ifelse(Study == "This study", "red", "black"))) +
  geom_point() +
  scale_x_continuous(breaks = pretty_breaks(n = 3)) +
  geom_errorbar(aes(xmin = lower, xmax = higher)) +
  scale_color_identity() +
  facet_wrap(~IFT, ncol = 4) +
  labs(x = "Irrigation efficiency", y = "") +
  theme_AP()
```



4.3 Overlap between irrigation efficiencies

```
# CHECK OVERLAP ---------------------------------------------------------------

dd <- uncertainty.dt[!Continent == "Oceania"][Study == "Rohwer et al. approach"] %>%
  split(., .$Continent, drop = TRUE)

overlap.dt <- lapply(dd, function(x) split(x, x$IFT, drop = TRUE)) %>%
  lapply(., function(x) lapply(x, function(y) y[, V1])) %>%
  lapply(., function(x) overlap(x)$OV)

overlap.dt
```

```
## $Africa
## Surface-Sprinkler     Surface-Mixed   Sprinkler-Mixed
##         0.2642237         0.4604639         0.4606540
##
## $Americas
## Surface-Mixed
##     0.4477437
##
## $Asia
## Surface-Micro Surface-Mixed   Micro-Mixed
##    0.05075313    0.44599065    0.06876229
##
## $Europe
## Surface-Sprinkler     Surface-Mixed   Sprinkler-Mixed
##         0.2616758         0.4542842         0.4650725
```

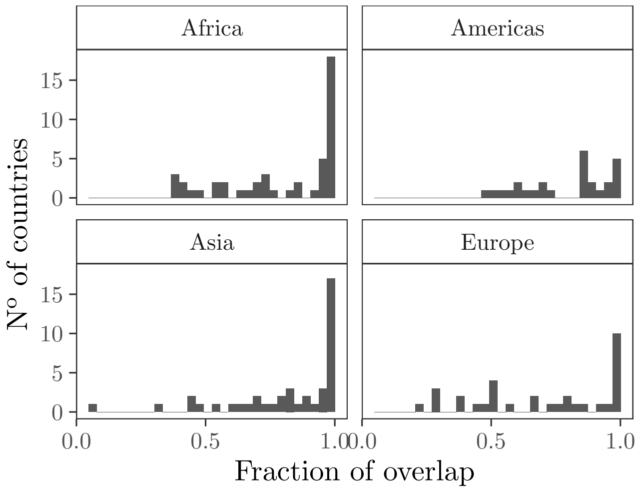
```r
ff <- uncertainty.dt[!Continent == "Oceania"] %>%
  .[Country %in% intersect(rohwer[, Country], jager[, Country])] %>%
  split(., .$Country, drop = TRUE) %>%
  lapply(., function(x) split(x, x$Approach, drop = TRUE)) %>%
  lapply(., function(x) lapply(x, function(y) y[, V1])) %>%
  lapply(., function(x) overlap(x)$OV) %>%
  lapply(., data.table) %>%
  rbindlist(., idcol = "Country") %>%
  .[, Continent:= countrycode(.[, Country],
                              origin = "country.name",
                              destination = "continent")]

list_continents <- list(c("Africa", "Asia"), c("Americas", "Europe"))

# PLOT OVERLAP ------------

dd <- list()
for(i in 1:length(list_continents)) {
  dd[[i]] <- ff[Continent %in% list_continents[[i]]] %>%
    ggplot(., aes(reorder(Country, V1), V1)) +
    geom_point() +
    scale_color_discrete(name = "GM") +
    labs(y = "Overlap", x = "") +
    facet_wrap(~Continent, scales = "free_y") +
    coord_flip() +
    theme_AP()
}

dd
```

```
## [[1]]
```

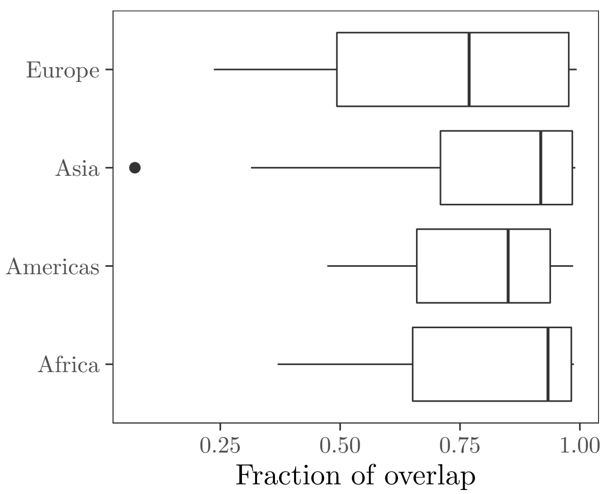
Africa
Asia
Mali
Niger
Gambia
Burundi
Rwanda
Angola
Sudan
Somalia
Eritrea
Guinea-Bissau
Central African Republic
Liberia
Djibouti
Nigeria
Senegal
Equatorial Guinea
Madagascar
Sierra Leone
Ethiopia
Zambia
Guinea
Mauritania
Uganda
Swaziland
Tunisia
Malawi
Chad
Egypt
Mozambique
Benin
Togo
Ghana
Morocco
Cameroon
Ivory Coast
Namibia
Zimbabwe
Libya
Burkina Faso
Algeria
Gabon
Tanzania
South Africa
Botswana
Lesotho
Kenya
North Korea
Tajikistan
Pakistan
Vietnam
Kyrgyzstan
Uzbekistan
Yemen
Bhutan
Turkmenistan
Bangladesh
Thailand
South Korea
Nepal
Cambodia
Indonesia
Laos
Philippines
Malaysia
Afghanistan
India
Brunei
China
Lebanon
Armenia
Iran
Kuwait
Georgia
Turkey
Cyprus
Qatar
Kazakhstan
Saudi Arabia
Japan
United Arab Emirates
Israel
Syria
Jordan
Azerbaijan
Iraq
Sri Lanka
Mongolia
Oman
0.25 0.50 0.75 1.00
0.25 0.50 0.75 1.00
Overlap


```
##
## [[2]]
```


```
# PLOT OVERLAP AS HISTOGRAMS AND BOXPLOTS  ---------------------------------------

ggplot(ff, aes(V1)) +
  geom_histogram() +
  facet_wrap(~Continent) +
  scale_x_continuous(breaks = pretty_breaks(n = 3)) +
  theme_AP() +
  labs(x = "Fraction of overlap", y = "Nº of countries")
```




```
ggplot(ff, aes(Continent, V1)) +
  geom_boxplot() +
  coord_flip() +
  theme_AP() +
  labs(y = "Fraction of overlap", x = "")
```



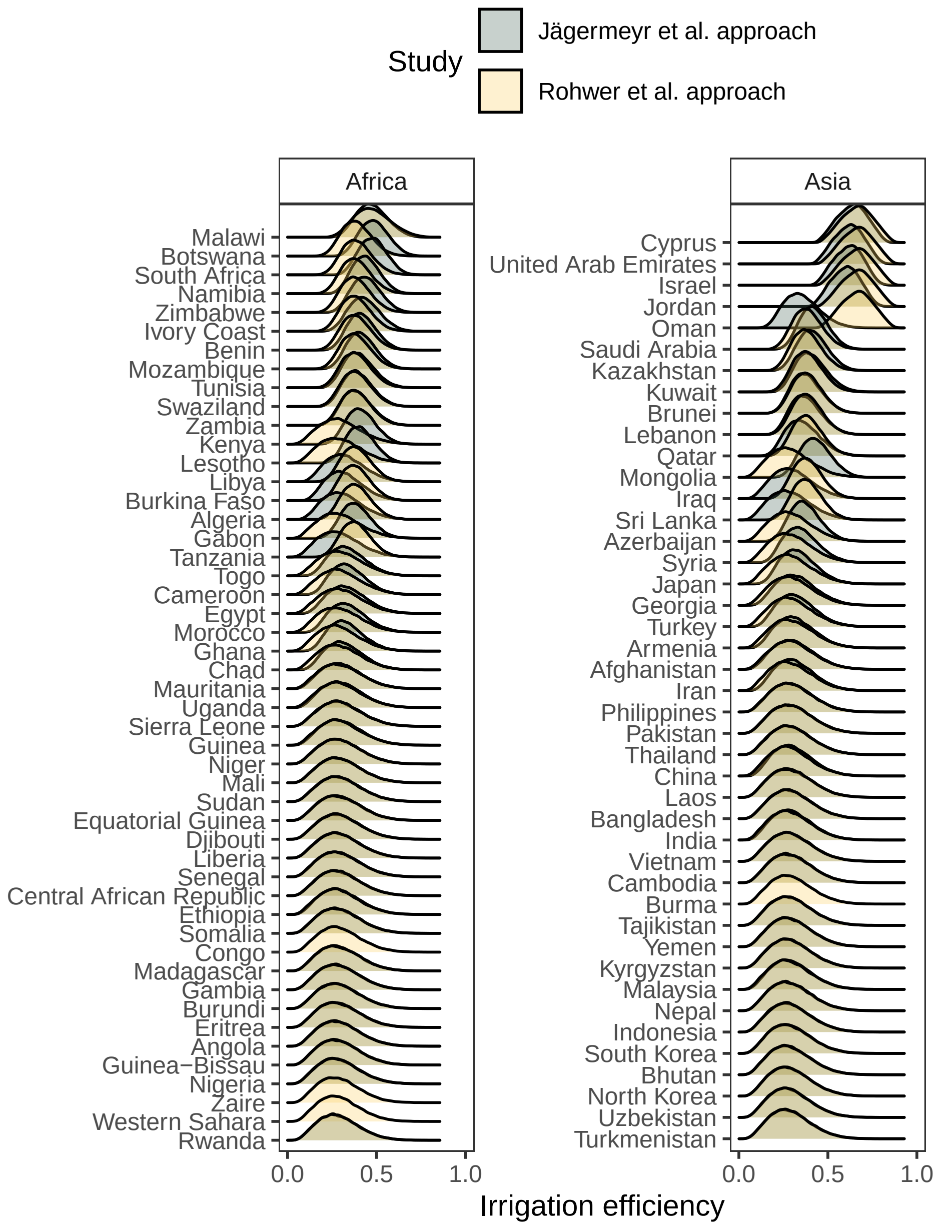

```
# CHECK CORRESPONDENCE BETWEEN SHARES OF IFT AND PREDOMINANT TECHNOLOGY ----------

# Retrieve countries where overlap is <0.3
merge(jager, rohwer, by = c("Country")) %>%
  .[Country %in% ff[V1 < 0.3][, Country]] %>%
  .[, .(Country, Surface_fraction, Sprinkler_fraction, Drip_fraction, IFT)]
```

```
##      Country Surface_fraction Sprinkler_fraction Drip_fraction       IFT
## 1: Macedonia            0.891              0.091         0.018 Sprinkler
## 2:   Moldova            0.298              0.636         0.066   Surface
## 3:      Oman            0.793              0.113         0.094     Micro
## 4:  Slovenia            0.000              0.693         0.307     Mixed
## 5:     Spain            0.297              0.226         0.478     Mixed
```

```r
# PLOT UNCERTAINTY -------------------------------------------------------------

gg <- list()
for (i in 1:length(list_continents)) {
  gg[[i]] <- ggplot(uncertainty.dt[Continent %in% list_continents[[i]]],
                    aes(x = V1, y = fct_reorder(Country, V1), fill = Study)) +
    geom_density_ridges(scale = 2, alpha = 0.3) +
    labs(x = "Irrigation efficiency", y = "") +
    facet_wrap(~Continent, scales = "free") +
    scale_x_continuous(breaks = pretty_breaks(n = 3),
                       limits = c(0, 1)) +
    scale_fill_manual(values = wes_palette("Chevalier1")) +
    theme_AP() +
    theme(legend.position = "top") +
    guides(fill = guide_legend(nrow = 2, byrow = TRUE))
}
```

```r
# MERGE PLOTS ------------------------------------------------------------------

gg
```

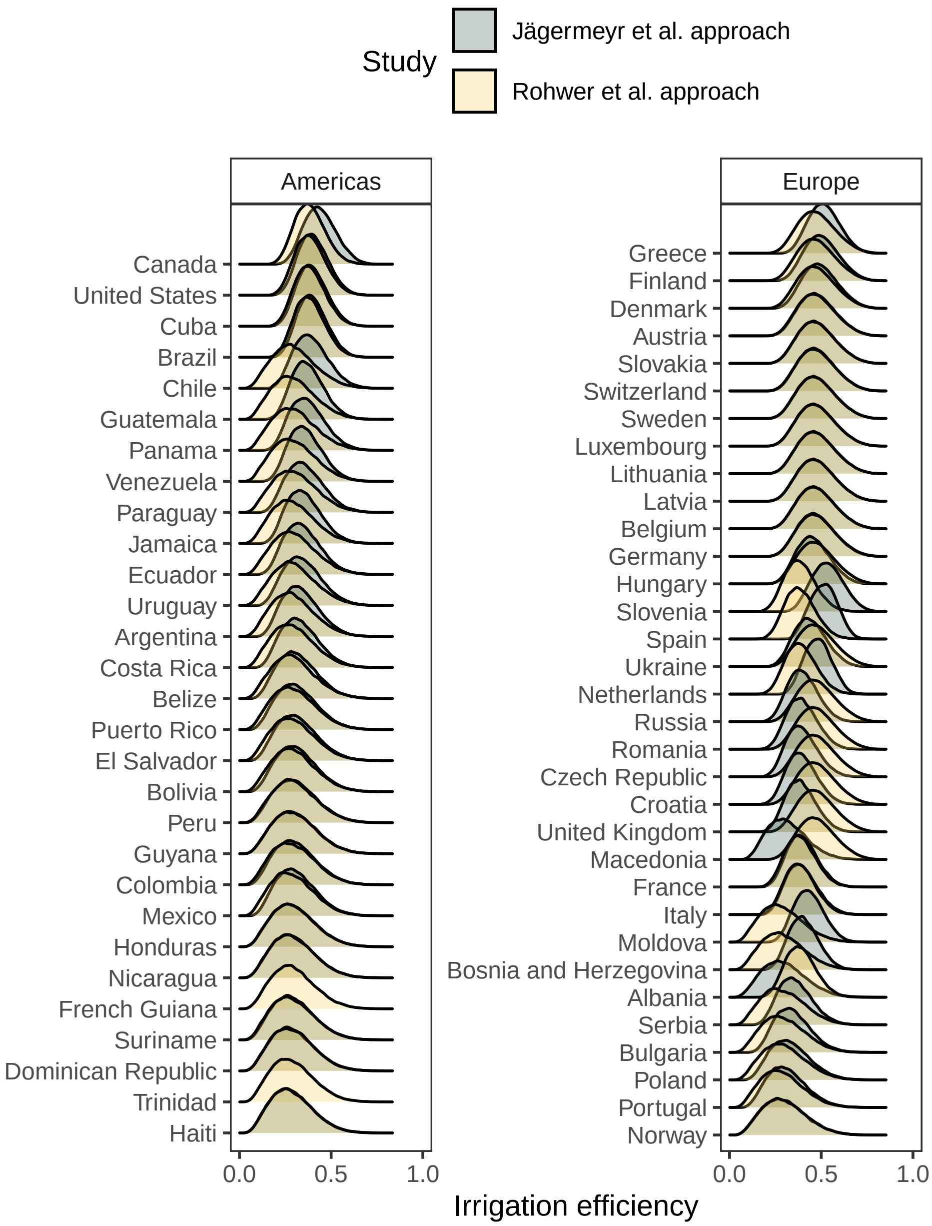
```
## [[1]]

## Picking joint bandwidth of 0.0116

## Picking joint bandwidth of 0.0117
```




```
##
## [[2]]
```

```
## Picking joint bandwidth of 0.0119
```

```
## Picking joint bandwidth of 0.0107
```



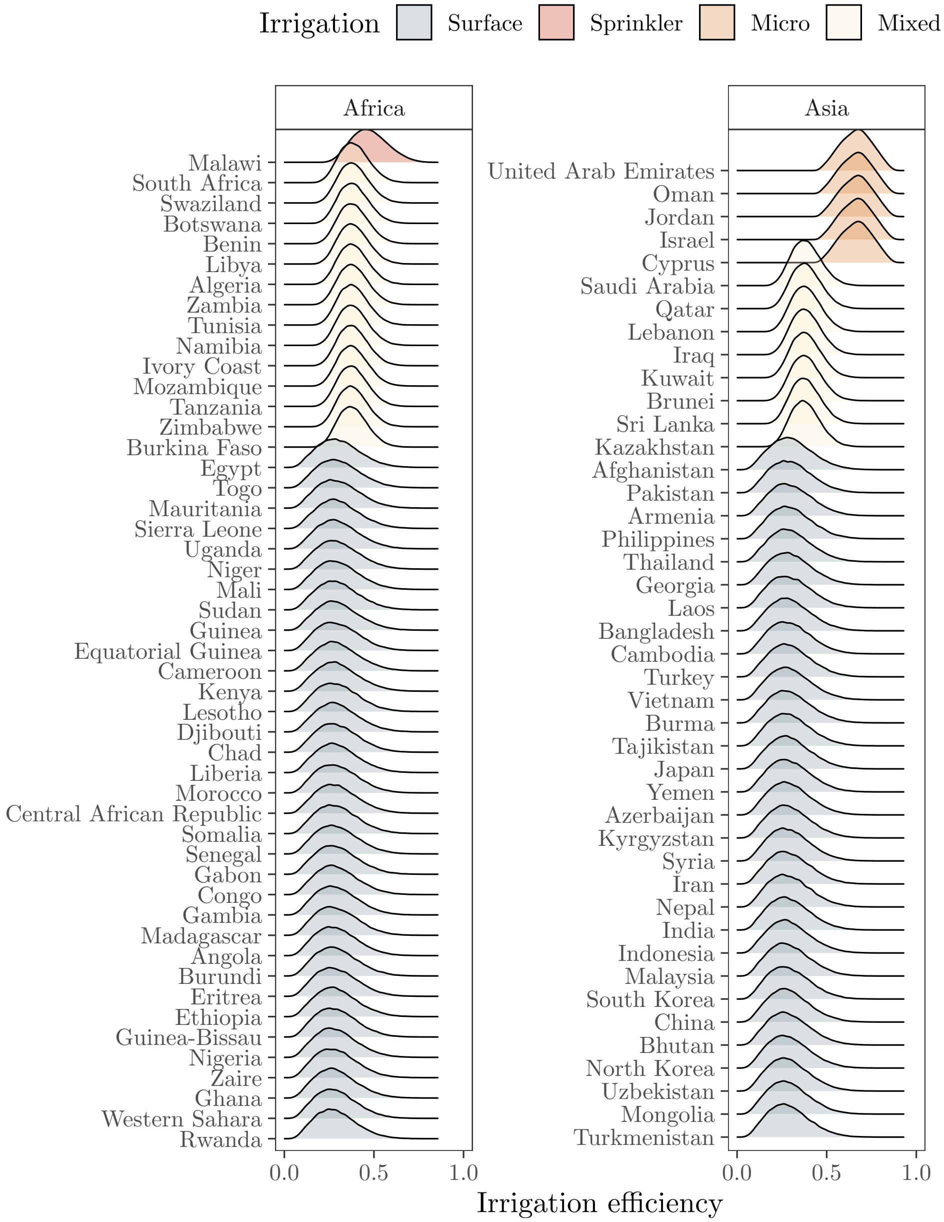

```
# PLOT UNCERTAINTY IN EACH IRRIGATION TECHNOLOGY --------------------------------

gg <- list()

for(i in 1:length(list_continents)) {
  gg[[i]] <- uncertainty.dt[Approach == "Rohwer et al. 2007"][Continent %in% list_continents[[
    ggplot(.,aes(x = V1, y = fct_reorder(Country, V1), fill = IFT)) +
    geom_density_ridges(scale = 2, alpha = 0.3) +
    labs(x = "Irrigation efficiency", y = "") +
    facet_wrap(~Continent, scales = "free") +
    scale_x_continuous(breaks = pretty_breaks(n = 3),
                       limits = c(0, 1)) +
    theme_AP() +
```

```r
    theme(legend.position = "top")
  if(i == 1) {
    gg[[i]] <- gg[[i]] +
      scale_fill_manual(values = c("#899DA4", "#C93312", "#DC863B", "#FAEFD1"),
                        labels = c("Surface", "Sprinkler", "Micro", "Mixed"),
                        name = "Irrigation")
  } else if(i == 2) {
    gg[[i]] <- gg[[i]] +
      scale_fill_manual(values = c("#899DA4", "#C93312", "#FAEFD1"),
                        labels = c("Surface", "Sprinkler", "Mixed"),
                        name = "Irrigation")
  }
}

gg
```

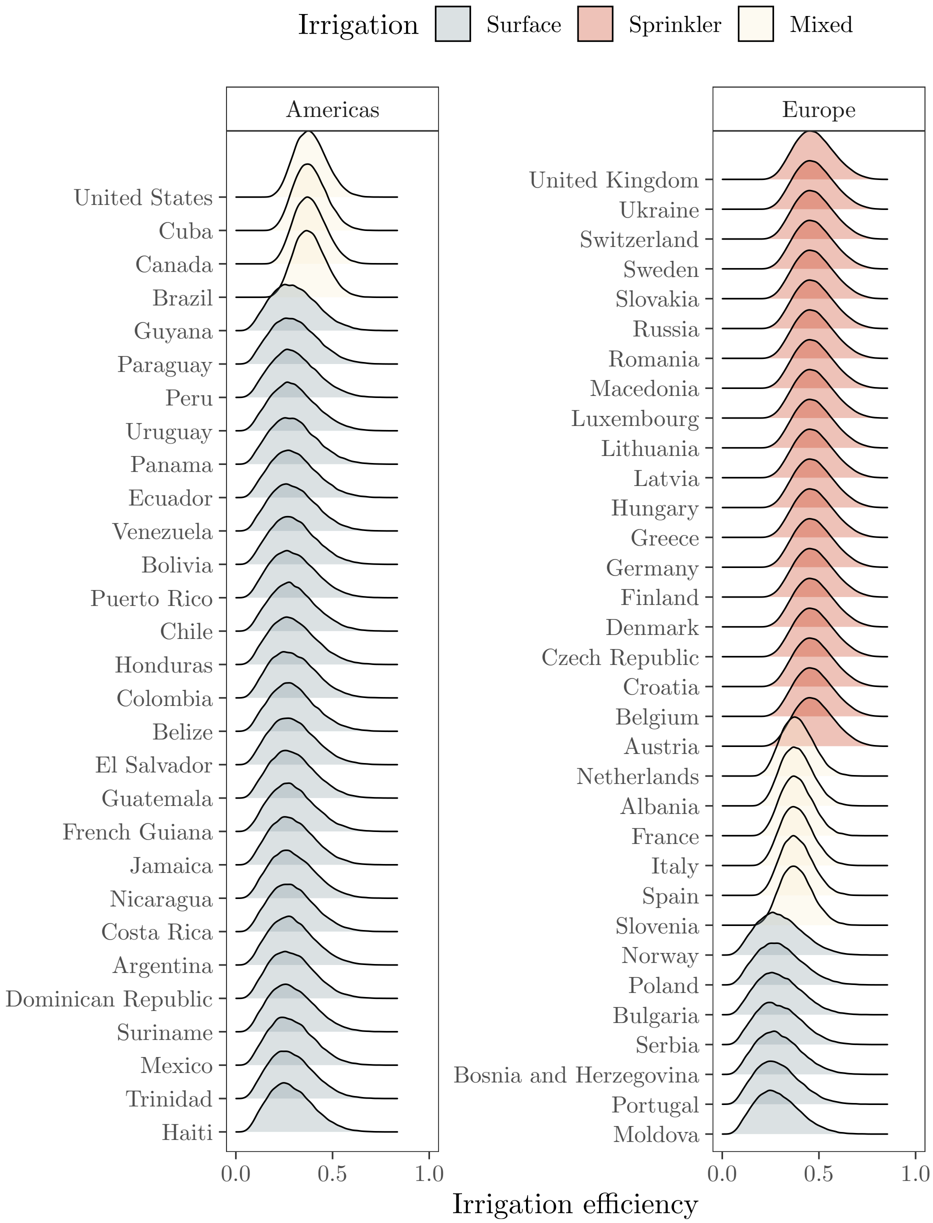
```
## [[1]]
```

```
## Picking joint bandwidth of 0.0118
```

```
## Picking joint bandwidth of 0.0119
```




```
##
## [[2]]

## Picking joint bandwidth of 0.0124

## Picking joint bandwidth of 0.0112
```



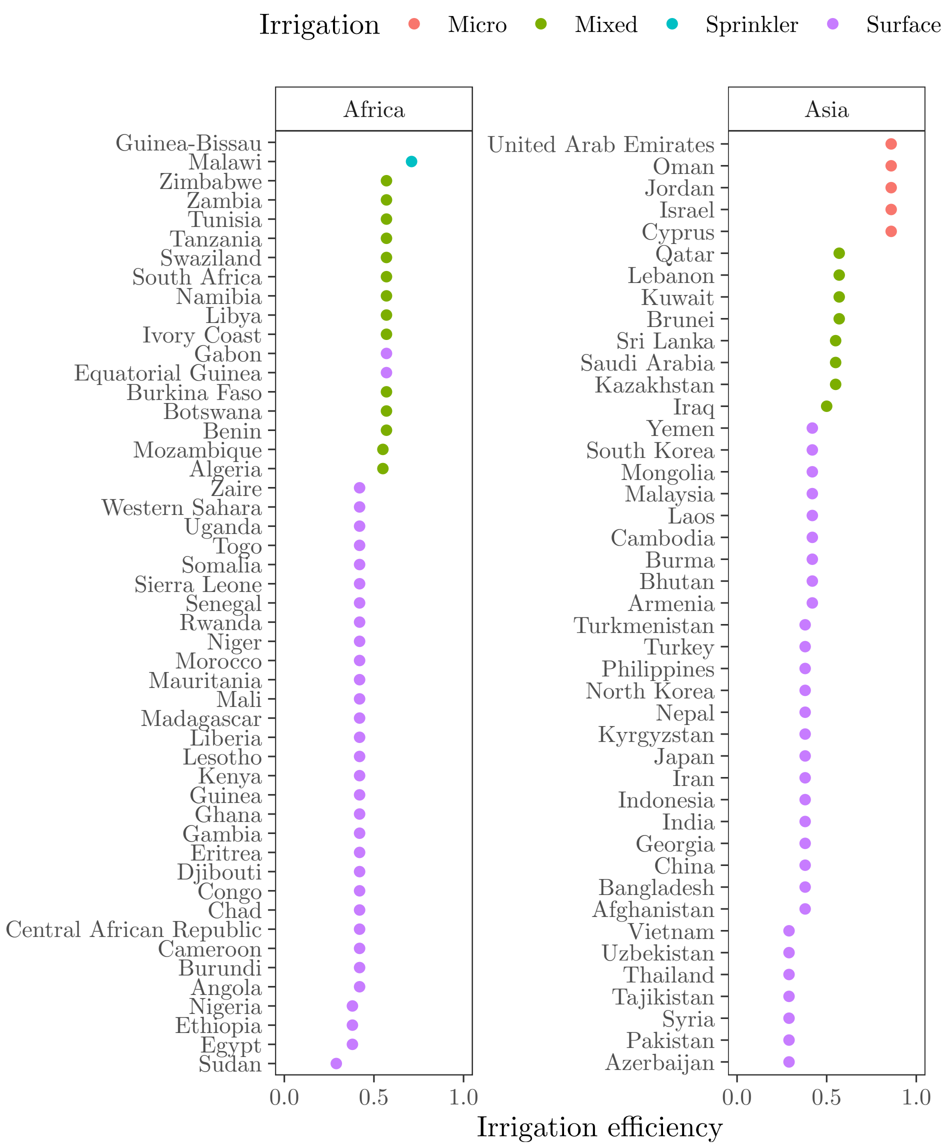

```
# PLOT ROHWER ET AL.'S IRRIGATION EFFICIENCY VALUES -----------------------------

rohwer[, Continent:= countrycode(rohwer[, Country], origin = "country.name",
                                 destination = "continent")]
```

```
## Warning in countrycode_convert(sourcevar = sourcevar, origin = origin, destination = dest,
```

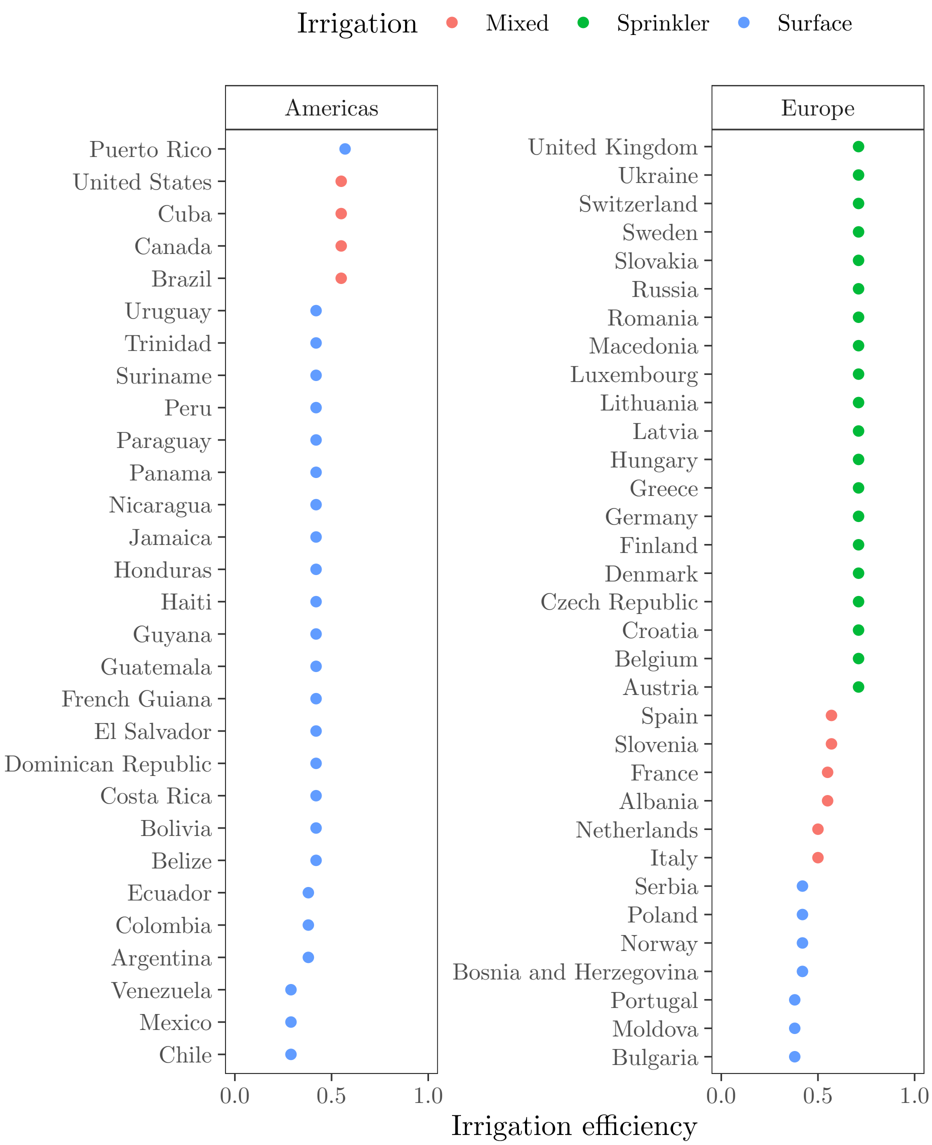
```
dd <- list()
for (i in 1:length(list_continents)) {
  dd[[i]] <- ggplot(rohwer[Continent %in% list_continents[[i]]],
                    aes(x = Ep, y = fct_reorder(Country, Ep), color = IFT)) +
    geom_point() +
    labs(x = "Irrigation efficiency", y = "") +
    scale_x_continuous(breaks = pretty_breaks(n = 3),
```

```
                        limits = c(0, 1)) +
    facet_wrap(~Continent, scales = "free") +
    scale_color_discrete(name = "Irrigation") +
    theme_AP()
}

dd
```

```
## [[1]]

## Warning: Removed 1 rows containing missing values (geom_point).
```

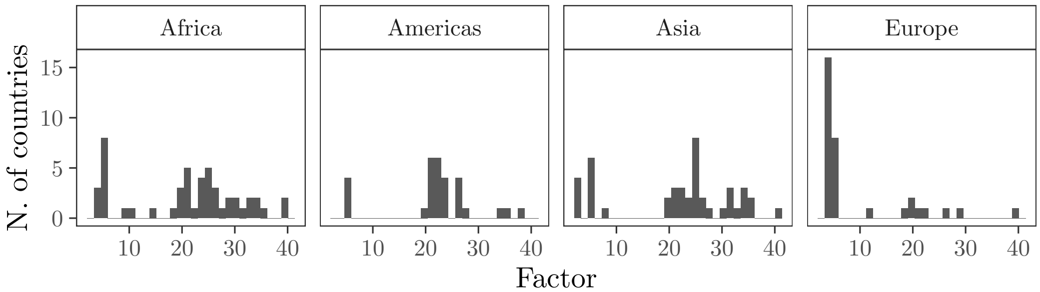



```
##
## [[2]]
```




```r
# CALCULATE THE UNCERTAINTY IN THE RANGES ----------------------------------------

selection_continents <- c("Africa", "Asia", "Americas", "Europe")

factor_unc <- uncertainty.dt[, .(min = min(V1), max = max(V1)), .(Continent, Country)] %>%
  .[Continent %in% selection_continents] %>%
  .[, factor:= max / min]

ggplot(factor_unc, aes(factor)) +
  geom_histogram() +
  facet_wrap(~Continent, ncol = 4) +
  labs(x = "Factor", y = "N. of countries") +
  theme_AP()
```

```
## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.
```




```r
# Number of countries whose irrigation water withdrawals fluctuate a factor of x
# due to uncertainty in irrigation efficiency
factor_unc %>%
  .[, factor:= floor(max / min)] %>%
  .[, .(number.countries = .N), factor] %>%
  .[order(factor)] %>%
  print()
```

```
##     factor number.countries
##  1:      2                4
##  2:      3               15
##  3:      4               27
##  4:      5                3
##  5:      7                1
##  6:      9                1
##  7:     10                1
##  8:     12                1
##  9:     14                1
## 10:     18                1
## 11:     19                6
## 12:     20               11
## 13:     21               11
## 14:     22                7
## 15:     23                9
## 16:     24               11
## 17:     25                6
## 18:     26                7
## 19:     27                1
## 20:     28                3
## 21:     29                3
## 22:     30                2
## 23:     31                4
## 24:     32                1
## 25:     33                4
## 26:     34                5
## 27:     35                3
## 28:     37                1
## 29:     38                1
## 30:     39                2
```

```
## 31:     40                 1
##     factor number.countries
```

4.4 Retrieve data from ISIMIP

```r
# FUNCTIONS TO EXTRACT DATA FROM .NC FILES --------------------------------------

coords2country = function(points) {
  countriesSP <- rworldmap::getMap(resolution = 'low')
  pointsSP = sp::SpatialPoints(points, proj4string=CRS(proj4string(countriesSP)))
  indices = sp::over(pointsSP, countriesSP)
  indices$ADMIN
}

# Function to load and extract data from .nc files from ISIMIP
open_nc_files <- function(file, dname, selected.years, vec) {
  ncin <- nc_open(file)
  # get longitude, latitude, time
  lon <- ncvar_get(ncin, "lon")
  lat <- ncvar_get(ncin, "lat")
  # Get variable
  tmp_array <- ncvar_get(ncin, dname)
  m <- lapply(selected.years, function(x) vec[[x]])

  out <- lapply(m, function(x) {
    tmp_slice <- lapply(x, function(y) tmp_array[, , y])
    # create dataframe -- reshape data
    # matrix (nlon*nlat rows by 2 cols) of lons and lats
    lonlat <- as.matrix(expand.grid(lon,lat))
    # vector of `tmp` values
    tmp_vec <- lapply(tmp_slice, function(x) as.vector(x))
    # create dataframe and add names
    tmp_df01 <- lapply(tmp_vec, function(x) data.frame(cbind(lonlat, x)))
    names(tmp_df01) <- x
    da <- lapply(tmp_df01, data.table) %>%
      rbindlist(., idcol = "month") %>%
      na.omit()
    # Convert coordinates to country
    Country <- coords2country(da[1:nrow(da), 2:3])
    df <- cbind(Country, da)
    setDT(df)
    out <- na.omit(df)[, .(Water.Withdrawn = sum(x)), Country]
    out[, Water.Withdrawn:= Water.Withdrawn * 10000]
    out[, Continent:= countrycode(out[, Country],
                                  origin = "country.name",
                                  destination = "continent")] %>%
      .[, Code:= countrycode(out[, Country],
```

```r
                              origin = "country.name",
                              destination = "un")] %>%
      .[, Country:= countrycode(out[, Code],
                                origin = "un",
                                destination = "country.name")] %>%
      .[!Continent == "Oceania"]
    setcolorder(out, c("Country", "Continent", "Code", "Water.Withdrawn"))
  })
  return(out)
}
```

```r
# READ IN NC FILES -------------------------------------------------------------

# Define settings
vecs <- 1:((2010 - 1970) * 12)
vec <- split(vecs, ceiling(seq_along(vecs) / 12))
names(vec) <- 1971:2010
selected.years <- "2010"
dname <- "pirrww"

files <- list("h08_wfdei_nobc_hist_varsoc_co2_pirrww_global_monthly_1971_2010.nc",
              "pcr-globwb_wfdei_nobc_hist_varsoc_co2_pirrww_global_monthly_1971_2010.nc",
              "lpjml_wfdei_nobc_hist_varsoc_co2_pirrww_global_monthly_1971_2010.nc",
              "watergap2_wfdei_nobc_hist_varsoc_co2_pirrww_global_monthly_1971_2010.nc")

names.isimip <- c("H08", "PCR-GLOBWB", "LPJmL", "WaterGap")

isimip.dt <- mclapply(files, function(x)
  open_nc_files(file = x, dname = dname, selected.years = selected.years, vec = vec),
  mc.cores = detectCores() * 0.75)
```

```r
# EXTRACT CORRECTIVE COEFFICIENTS FOR IRRIGATION EFFICIENCY FOR LPJML ------------

ncin <- nc_open("irrigation_project_efficiencies.nc")
lon <- ncvar_get(ncin, "lon")
lat <- ncvar_get(ncin, "lat")
tmp_array <- ncvar_get(ncin)
lonlat <- as.matrix(expand.grid(lon,lat))
da <- na.omit(cbind(lonlat, as.vector(tmp_array))) %>%
  data.frame() %>%
  na.omit()
Country <- coords2country(da[1:nrow(da), 1:2])
lpjml_efficiencies <- cbind(Country, da) %>%
  na.omit() %>%
  data.table() %>%
  .[, .(Ep = mean(V3)), Country]
```

```r
# ARRANGE NC FILES --------------------------------------------------------------

names(isimip.dt) <- names.isimip

isimip.dt <- lapply(isimip.dt, function(x) rbindlist(x)) %>%
  rbindlist(., idcol = "Model") %>%
  na.omit() %>%
  # To correct for duplicate country in Cyprus
  .[, .(Water.Withdrawn = mean(Water.Withdrawn)), .(Model, Country, Continent, Code)]

lpjml_harmonized <- merge(isimip.dt[Model == "LPJmL"], lpjml_efficiencies, all.x = TRUE) %>%
  .[, Water.Withdrawn:= Water.Withdrawn * Ep] %>%
  .[, Ep:= NULL]

isimip.dt <- rbind(isimip.dt[!Model == "LPJmL"], lpjml_harmonized)

fwrite(isimip.dt, "isimip.dt")
```

```r
# MERGE UNCERTAINTY IN EP WITH ISIMIP DATA --------------------------------------

efficiency.dt <- copy(uncertainty.dt) %>%
  setnames(., "V1", "Ep")

ghm.dt <- dcast(isimip.dt, Country + Continent + Code ~ Model, value.var = "Water.Withdrawn")
full.dt <- merge(efficiency.dt, ghm.dt, by = c("Country", "Continent"), all.x = TRUE) %>%
  .[, (names.isimip):= lapply(.SD, function(x) x / Ep), .SDcols = names.isimip]
tmp.dt <- melt(full.dt, measure.vars = names.isimip, variable.name = "Model",
               value.name = "IWW_corrected")
ghm.large <- melt(ghm.dt, measure.vars = names.isimip, variable.name = "Model",
     value.name = "IWW")
gm.uncertainty <- tmp.dt[, .(min = min(IWW_corrected), max = max(IWW_corrected)),
                         .(Country, Continent, Model)]
gm.dt <- merge(ghm.large, gm.uncertainty)
```

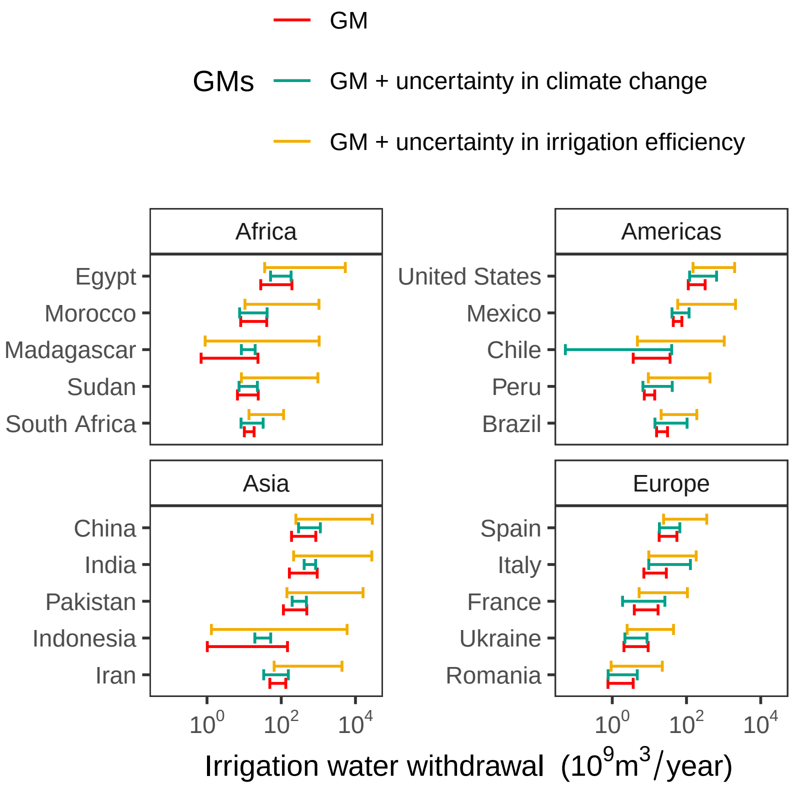
4.5 Retrieve data from ISIMIP (climate change in 2050)

```r
# READ IN FILES ON CLIMATE CHANGE UNCERTAINTY (2050) ----------------------------

files <- list(
  "watergap2_miroc5_ewembi_rcp85_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "watergap2_miroc5_ewembi_rcp60_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "watergap2_miroc5_ewembi_rcp45_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "watergap2_miroc5_ewembi_rcp26_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "lpjml_miroc5_ewembi_rcp85_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "lpjml_miroc5_ewembi_rcp60_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "lpjml_miroc5_ewembi_rcp26_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "pcr-globwb_miroc5_ewembi_rcp60_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
```

```r
  "pcr-globwb_miroc5_ewembi_rcp26_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "h08_miroc5_ewembi_rcp85_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "h08_miroc5_ewembi_rcp60_2005soc_co2_pirrww_global_monthly_2006_2099.nc",
  "h08_miroc5_ewembi_rcp26_2005soc_co2_pirrww_global_monthly_2006_2099.nc"
)

vecs <- 1:((2099 - 2005) * 12)
vec <- split(vecs, ceiling(seq_along(vecs) / 12))
names(vec) <- 2006:2099
dname <- "pirrww"
selected.years <- as.character(seq(2030, 2050, 10))

# Read in datasets
isimip.climate <- mclapply(
  files, function(x)
    open_nc_files(file = x, dname = dname, selected.years = selected.years, vec = vec),
  mc.cores = detectCores() * 0.75
)
```

```r
# ARRANGE DATASETS -------------------------------------------------------------

ghms <- c(rep("WaterGap", times = 4),
          rep("LPJmL", times = 3),
          rep("PCR-GLOBWB", times = 2),
          rep("H08", times = 3))

climate_scenario <- c(85, 60, 45, 26, 85, 60, 26, 60, 26, 85, 60, 26)
names.isimip <- paste(ghms, climate_scenario, sep = "/")

# Name the slots
names(isimip.climate) <- names.isimip

for(i in names(isimip.climate)) {
  names(isimip.climate[[i]]) <- selected.years
}

# Arrange data
isimip.climate.dt <- lapply(isimip.climate, function(x) rbindlist(x, idcol = "Year")) %>%
  rbindlist(., idcol = "Model") %>%
  .[!Continent == "Oceania"] %>%
  separate(., "Model", c("Model", "Climate scenario"), "/") %>%
  na.omit() %>%
  .[Year == 2050]

# Export
fwrite(isimip.climate.dt, "isimip.climate.dt.csv")
```

```r
# PLOT RANGES OF STRUCTURAL UNCERTAINTY AND RANGES OF
# STRUCTURAL UNCERTAINTY + UNCERTAINTY IN IRRIGATION EFFICIENCY +
# UNCERTAINTY IN CLIMATE CHANGE ---------------------------------------------

countries_list <- c("Egypt", "Sudan", "South Africa", "Morocco", "Madagascar",
                    "United States", "Mexico", "Brazil", "Chile", "Peru",
                    "India", "China", "Pakistan", "Iran", "Indonesia",
                    "Italy", "Spain", "France", "Ukraine", "Romania")

range.gm <- gm.dt %>%
  .[, .(min = min(IWW, na.rm = TRUE), max = max(IWW, na.rm = TRUE)),
    .(Country, Continent)] %>%
  .[, Approach:= "GM"]

range.study <- gm.dt %>%
  .[, .(min = min(min, na.rm = TRUE), max = max(max, na.rm = TRUE)),
    .(Country, Continent)] %>%
  .[, Approach:= "GM + uncertainty in irrigation efficiency"]

range.climate <- isimip.climate.dt %>%
  .[, .(min = min(Water.Withdrawn), max = max(Water.Withdrawn)),
    .(Country, Continent)] %>%
  .[, Approach:= "GM + uncertainty in climate change"]

all.uncertainties <- rbind(range.gm, range.study, range.climate) %>%
  .[, mean:= (min + max) / 2]

# Substitute 0 by NA ----------------------------
all.uncertainties[all.uncertainties == 0] <- NA

all.uncertainties %>%
  .[Country %in% countries_list] %>%
  ggplot(., aes(reorder(Country, mean), mean, color = Approach)) +
  geom_errorbar(aes(ymin = min,
                    ymax = max),
                position = position_dodge(0.7)) +
  scale_y_log10(breaks = trans_breaks("log10", function(x) 10 ^ (2 * x)),
                labels = trans_format("log10", math_format(10 ^ .x))) +
  scale_color_manual(name = "GMs", values = wes_palette("Darjeeling1")) +
  labs(y = expression(paste("Irrigation water withdrawal ", " ", "(", 10^9, m^3/year, "", ")")),
       x = "") +
  facet_wrap(~Continent, scales = "free_y") +
  coord_flip() +
  theme_AP() +
  guides(color = guide_legend(nrow = 3, byrow = TRUE))
```

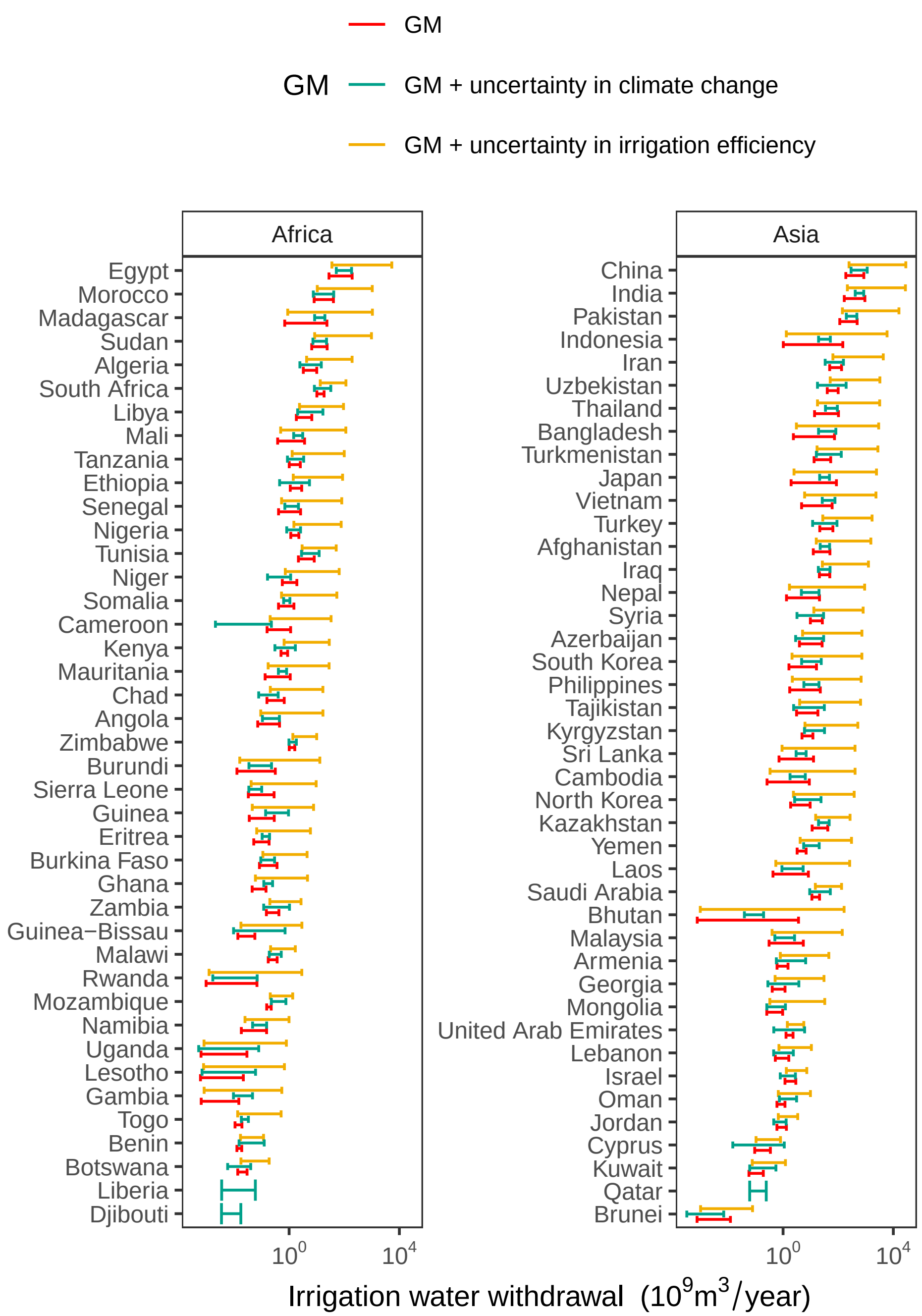



```
# EXPORT -----------
fwrite(all.uncertainties, "all.uncertainties.csv")
```

```
# PLOT RANGES OF STRUCTURAL UNCERTAINTY AND RANGES OF
# STRUCTURAL UNCERTAINTY + UNCERTAINTY IN IRRIGATION EFFICIENCY (COMPLETE) -------

vec1 <- all.uncertainties[Approach == "GM", Country]
vec2 <- all.uncertainties[Approach == "GM + uncertainty in climate change", Country]
vec3 <- all.uncertainties[Approach == "GM + uncertainty in irrigation efficiency", Country]
common_countries <- Reduce(intersect, list(vec1, vec2, vec3))

dd <- list()
for (i in 1:length(list_continents)) {
  dd[[i]] <- all.uncertainties %>%
    .[Country %in% common_countries] %>%
    na.omit() %>%
    .[Continent %in% list_continents[[i]]] %>%
    ggplot(., aes(reorder(Country, mean), mean, color = Approach)) +
    geom_errorbar(aes(ymin = min,
                      ymax = max),
                  position = position_dodge(0.7)) +
    scale_y_log10(breaks = trans_breaks("log10", function(x) 10 ^ (2 * x)),
                  labels = trans_format("log10", math_format(10 ^ .x))) +
    scale_color_manual(name = "GM", values = wes_palette("Darjeeling1")) +
    labs(y = expression(paste("Irrigation water withdrawal ", " ", "(", 10^9, m^3/year, "", ")"
         x = "") +
```

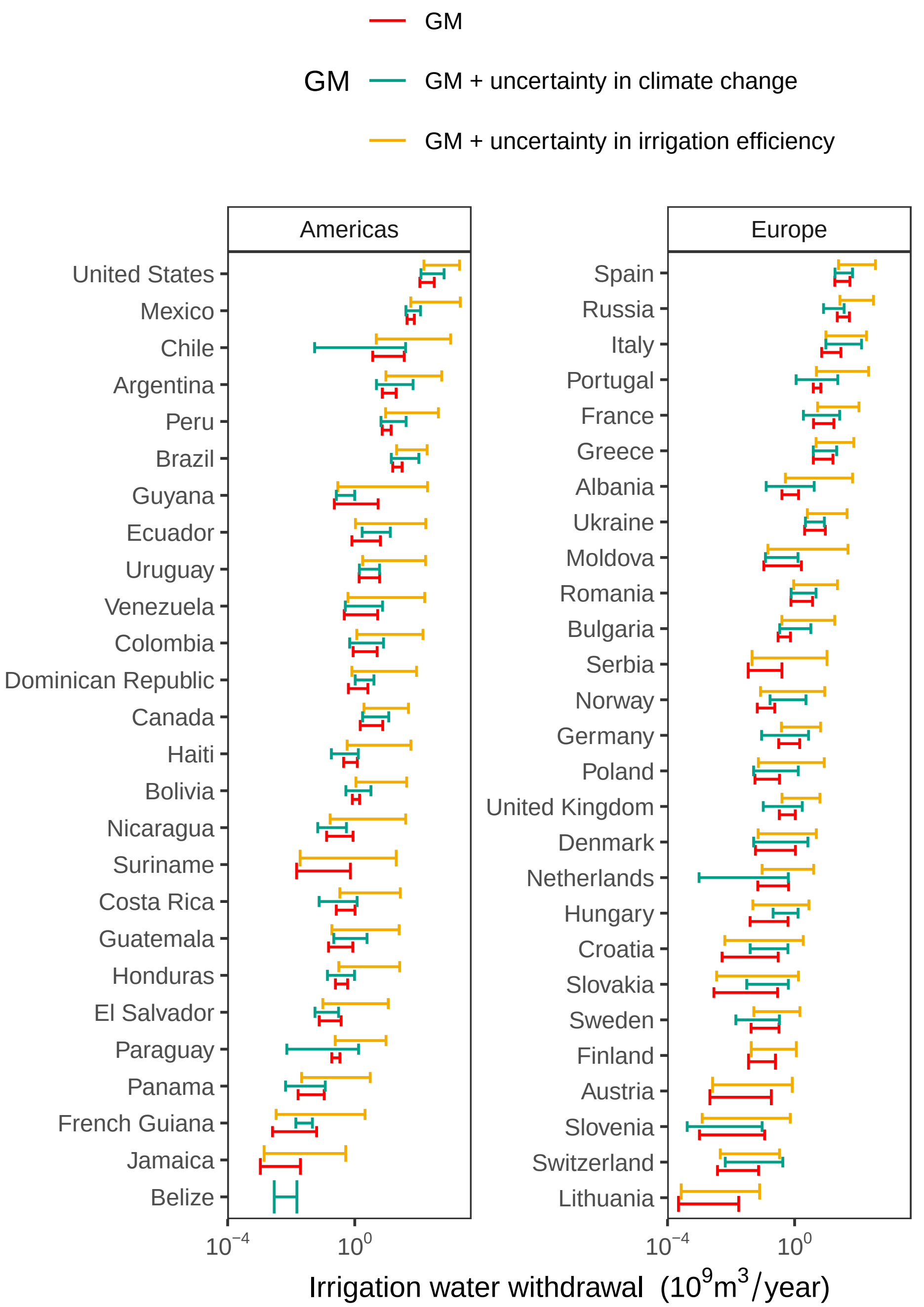
```
    facet_wrap(~Continent, scales = "free_y") +
    coord_flip() +
    theme_AP() +
    guides(color = guide_legend(nrow = 3, byrow = TRUE))
}

dd
```

```
## [[1]]
```




```
##
```

```
## [[2]]
```




```
# COMPARE RANGES ----------------------------------------------------------------

all.uncertainties[, range:= max - min]
dd <- dcast(all.uncertainties,Country + Continent ~ Approach, value.var = "range") %>%
  na.omit() %>%
  .[, maxCol:= max.col(.[, 3:5], ties.method = "first")]

# check which countries show the largest ranges in climate uncertainty
lapply(1:3, function(x) dd[maxCol == x])
```

```
## [[1]]
## Empty data.table (0 rows and 6 cols): Country,Continent,GM,GM + uncertainty in climate chang
##
## [[2]]
##                Country Continent          GM GM + uncertainty in climate change
## 1:               Benin    Africa 0.00634165                           0.1095379
## 2:              Cyprus      Asia 0.25356972                           1.0901057
## 3:         Switzerland    Europe 0.06956323                           0.4174803
## 4: United Arab Emirates      Asia 1.02446010                           5.5930987
##    GM + uncertainty in irrigation efficiency maxCol
## 1:                                 0.1006289      2
## 2:                                 0.7022605      2
## 3:                                 0.3293323      2
## 4:                                 4.2191107      2
##
## [[3]]
##          Country Continent         GM GM + uncertainty in climate change
##   1: Afghanistan      Asia 37.8147475                         26.5443113
##   2:     Albania    Europe  0.9324792                          4.0007740
##   3:     Algeria    Africa  6.7659506                         12.2469498
##   4:      Angola    Africa  0.3768065                          0.3377945
##   5:   Argentina  Americas 12.6584940                         63.6812769
##  ---
## 118:   Venezuela  Americas  4.8093549                          6.9755145
## 119:     Vietnam      Asia 55.5815237                         49.9370651
## 120:       Yemen      Asia  3.6273127                         14.8781794
## 121:      Zambia    Africa  0.2776971                          0.9126939
## 122:    Zimbabwe    Africa  0.5964828                          0.8408030
##      GM + uncertainty in irrigation efficiency maxCol
##   1:                               1515.858339      3
##   2:                                 66.132774      3
##   3:                                188.296820      3
##   4:                                 16.773342      3
##   5:                                535.053389      3
##  ---
## 118:                                158.353988      3
## 119:                               2342.467615      3
## 120:                                299.368661      3
## 121:                                  2.500587      3
## 122:                                  8.635619      3
```

5 Sensitivity analysis

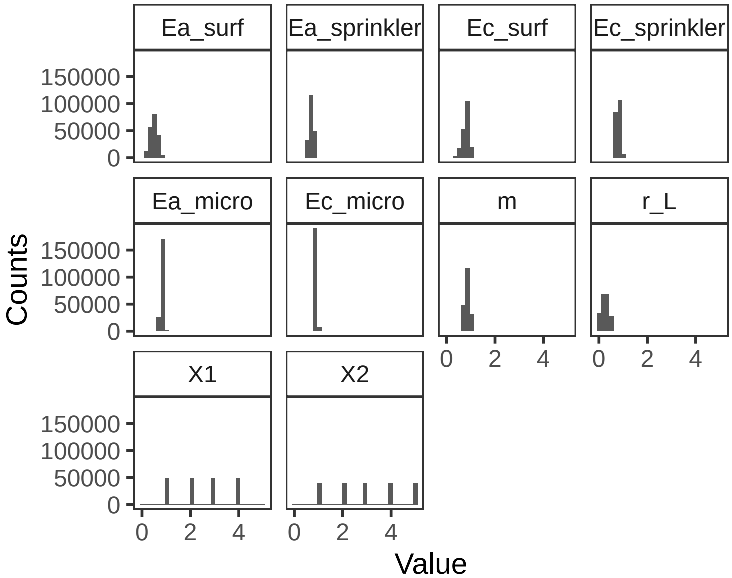
```
# SAMPLE MATRIX DISTRIBUTIONS -----------------------------------------------

# Define labels
label_facets <- c("Ea_surf" = "$E_{a_{su}}$",
```

```r
                  "Ec_surf" = "$E_{c_{su}}$",
                  "Ea_sprinkler" = "$E_{a_{sp}}$",
                  "Ec_sprinkler" = "$E_{c_{sp}}$",
                  "Ea_micro" = "$E_{a_{mi}}$",
                  "Ec_micro" = "$E_{c_{mi}}$",
                  "Proportion_large" = "$f_L$",
                  "m" = "$m$",
                  "r_L" = "$r_L$")

mat <- data.table(full_sample_matrix(IFT = "Jager", Country = "Spain")$matrix)
mat <- mat[, Proportion_large:= NULL]
```

```
## Warning in `[.data.table`(mat, , `:=`(Proportion_large, NULL)): Column
## 'Proportion_large' does not exist to remove
```

```r
melt(mat, measure.vars = colnames(mat)) %>%
  ggplot(., aes(value)) +
  geom_histogram() +
  labs(x = "Value", y = "Counts") +
  scale_x_continuous(breaks = pretty_breaks(n = 3)) +
  facet_wrap(~variable) +
  theme_AP()
```

```
## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.
```



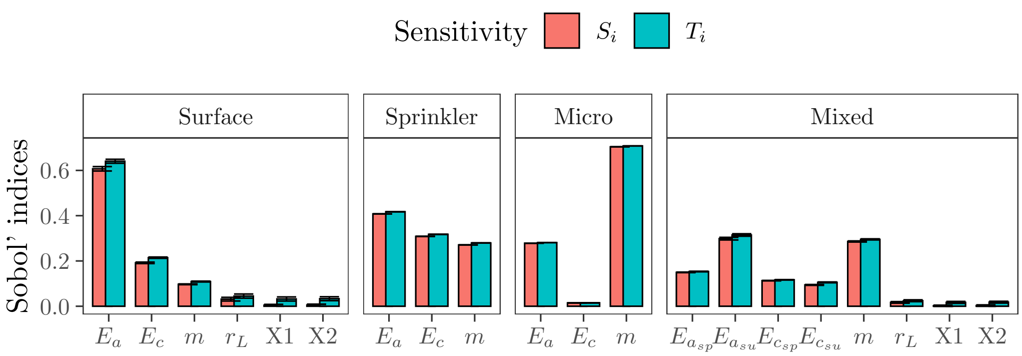

```r
# EXTRACT SOBOL' INDICES ---------------------------------------------------

ind <- lapply(y$`Rohwer et al. 2007`, function(x) x[["indices"]]$results)
names(ind) <- rohwer$Country
ind <- rbindlist(ind, idcol = "Country")

ind[, Continent:= countrycode(ind[, Country], origin = "country.name",
```

```
                                    destination = "continent")]
```

```
## Warning in countrycode_convert(sourcevar = sourcevar, origin = origin, destination = dest,
```

```
tmp.ift <- split(rohwer, rohwer$IFT)

out <- list()
for(i in names(tmp.ift)) {
  out[[i]] <- ind[Country %in% tmp.ift[[i]][, Country]]
}
```

```
# PLOT SOBOL' INDICES -------------------------------------------------------

ind.dt <- rbindlist(out, idcol = "IFT") %>%
  .[, IFT:= factor(IFT, levels = c("Surface", "Sprinkler", "Micro", "Mixed"))]

tmp <- ind.dt[, .(mean = mean(original), sd = sd(original)),
              .(sensitivity, parameters, IFT)]

tmp2 <- tmp[!IFT == "Mixed"][, parameters:= ifelse(parameters == "Ea_surf", "$E_a$",
                                                   ifelse(parameters == "Ec_surf", "$E_c$",
                                                          ifelse(parameters == "Ea_sprinkler",
                                                                 ifelse(parameters == "Ec_sprin
                                                                        ifelse(parameters == "
                                                                               ifelse(paramete

rbind(tmp[IFT == "Mixed"], tmp2) %>%
  ggplot(., aes(parameters, mean, fill = sensitivity), color = black) +
  geom_bar(stat = "identity", position = position_dodge(0.6), color = "black") +
  geom_errorbar(aes(ymin = mean - sd, ymax = mean + sd), position = position_dodge(0.6)) +
  scale_x_discrete(labels = label_facets) +
  scale_fill_discrete(name = "Sensitivity", labels = c("$S_i$", "$T_i$")) +
  labs(x = "", y = "Sobol' indices") +
  facet_grid(~IFT, space = "free_x", scale = "free_x") +
  theme_AP()
```




```
# EXTRACT SOBOL' INDICES FOR JAGER ------------------------------------------

jager.tmp <- lapply(y[["Jägermeyr et al. 2015"]], function(x) x$indices$results)
```

```r
names(jager.tmp) <- new.rohwer$Country

jager.ind <- rbindlist(jager.tmp, idcol = "Country") %>%
  .[, Continent:= countrycode(.[, Country],
                              origin = "country.name",
                              destination = "continent")] %>%
  .[, parameters:= ifelse(parameters == "Ea_surf", "E[a[s]]",
                         ifelse(parameters == "Ec_surf", "E[c[s]]",
                                ifelse(parameters == "Ea_sprinkler", "E[a[p]]",
                                       ifelse(parameters == "Ec_sprinkler", "E[c[p]]",
                                              ifelse(parameters == "Ea_micro", "E[a[m]]",
                                                     ifelse(parameters == "Ec_micro", "E[c[m]]
                                                            ifelse(parameters == "r_L", "r[L]"
                                                                   ifelse(parameters == "X1", 
                                                                          ifelse(parameters ==
```

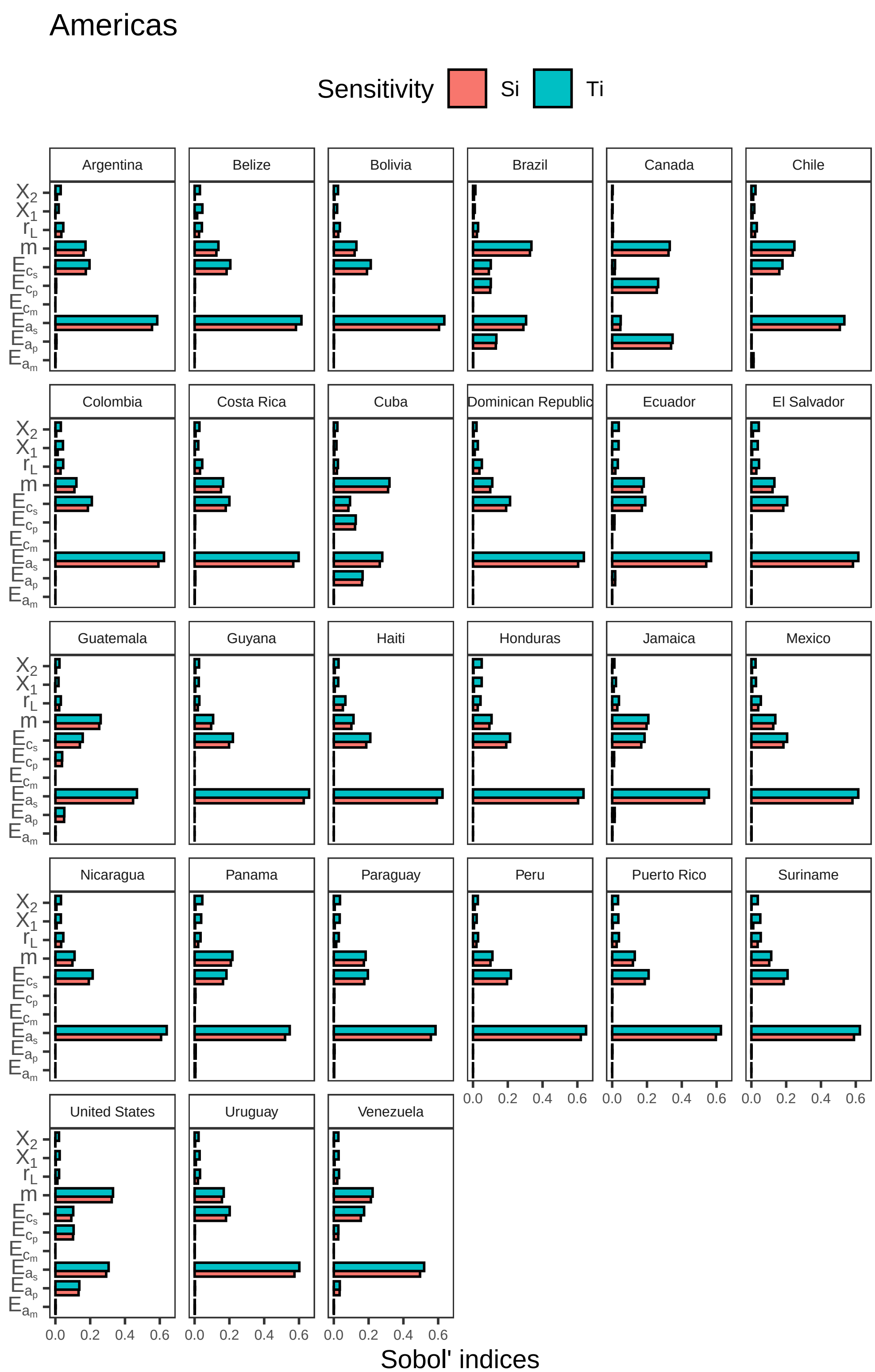
```
## Warning in countrycode_convert(sourcevar = sourcevar, origin = origin, destination = dest,
```

```r
Continent_vector <- c("Africa", "Americas", "Asia", "Europe")

lapply(Continent_vector, function(x)
  ggplot(jager.ind[Continent == x], aes(parameters, original, fill = sensitivity), color = bla
    geom_bar(stat = "identity", position = position_dodge(0.6), color = "black") +
    scale_fill_discrete(name = "Sensitivity", labels = c("Si", "Ti")) +
    labs(x = "", y = "Sobol' indices") +
    scale_x_discrete(labels = ggplot2:::parse_safe) +
    coord_flip() +
    scale_y_continuous(breaks = pretty_breaks(n = 3)) +
    facet_wrap(~Country) +
    theme_AP() +
    theme(strip.text.x = element_text(size = 6),
          axis.text.x = element_text(size = 6)) +
    ggtitle(x)
)
```

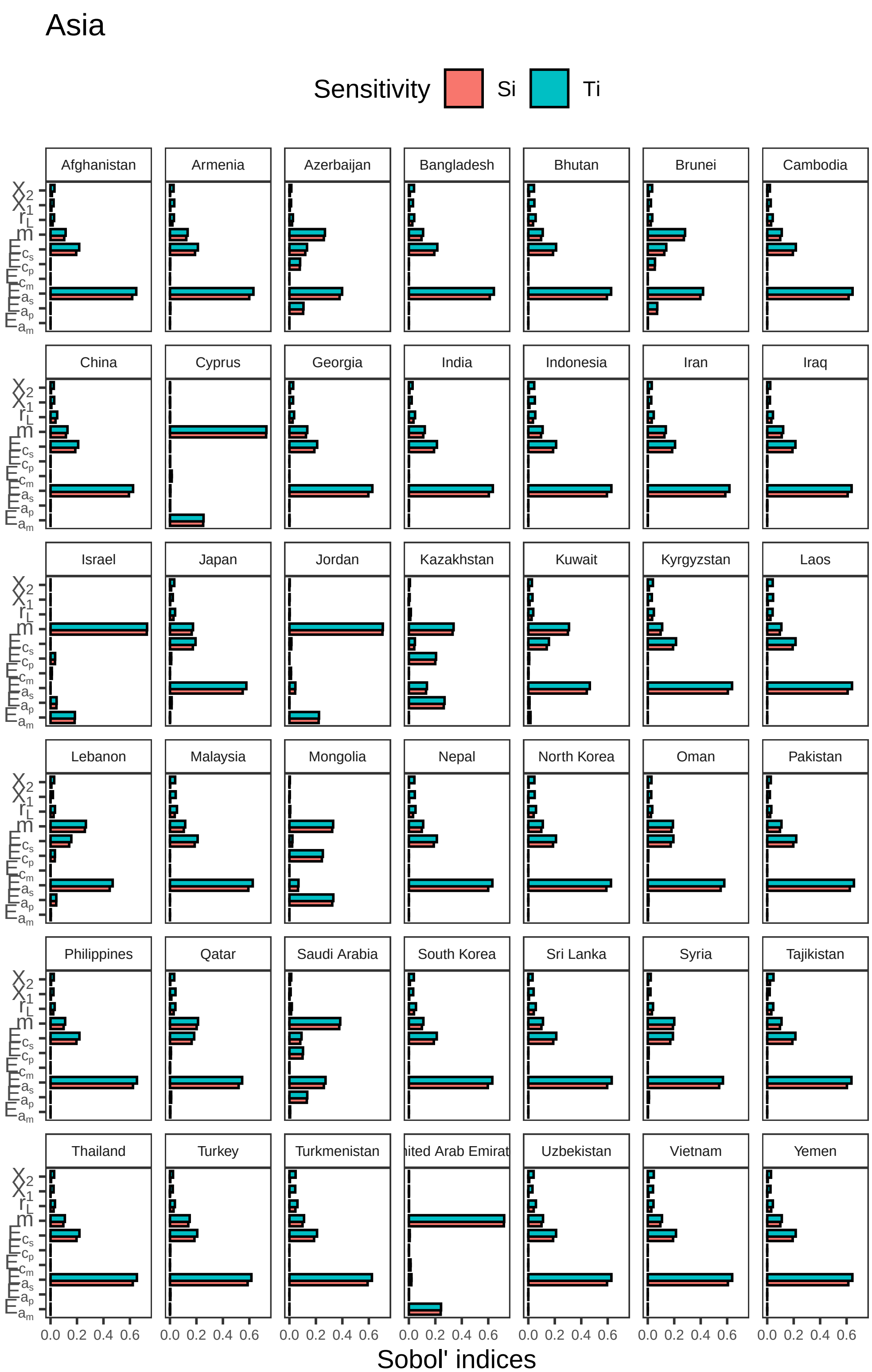
```
## [[1]]
```


Africa
Sensitivity
Si
Ti
Algeria
Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
ntral African Repu
Chad
Djibouti
Egypt
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Gambia
Ghana
Guinea
Guinea−Bissau
Ivory Coast
Kenya
Lesotho
Liberia
Libya
Madagascar
Malawi
Mali
Mauritania
Morocco
Mozambique
Namibia
Niger
Nigeria
Rwanda
Senegal
Sierra Leone
Somalia
South Africa
Sudan
Swaziland
Tanzania
Togo
Tunisia
Uganda
Zambia
Zimbabwe
0.0 0.2 0.4 0.6
Sobol' indices

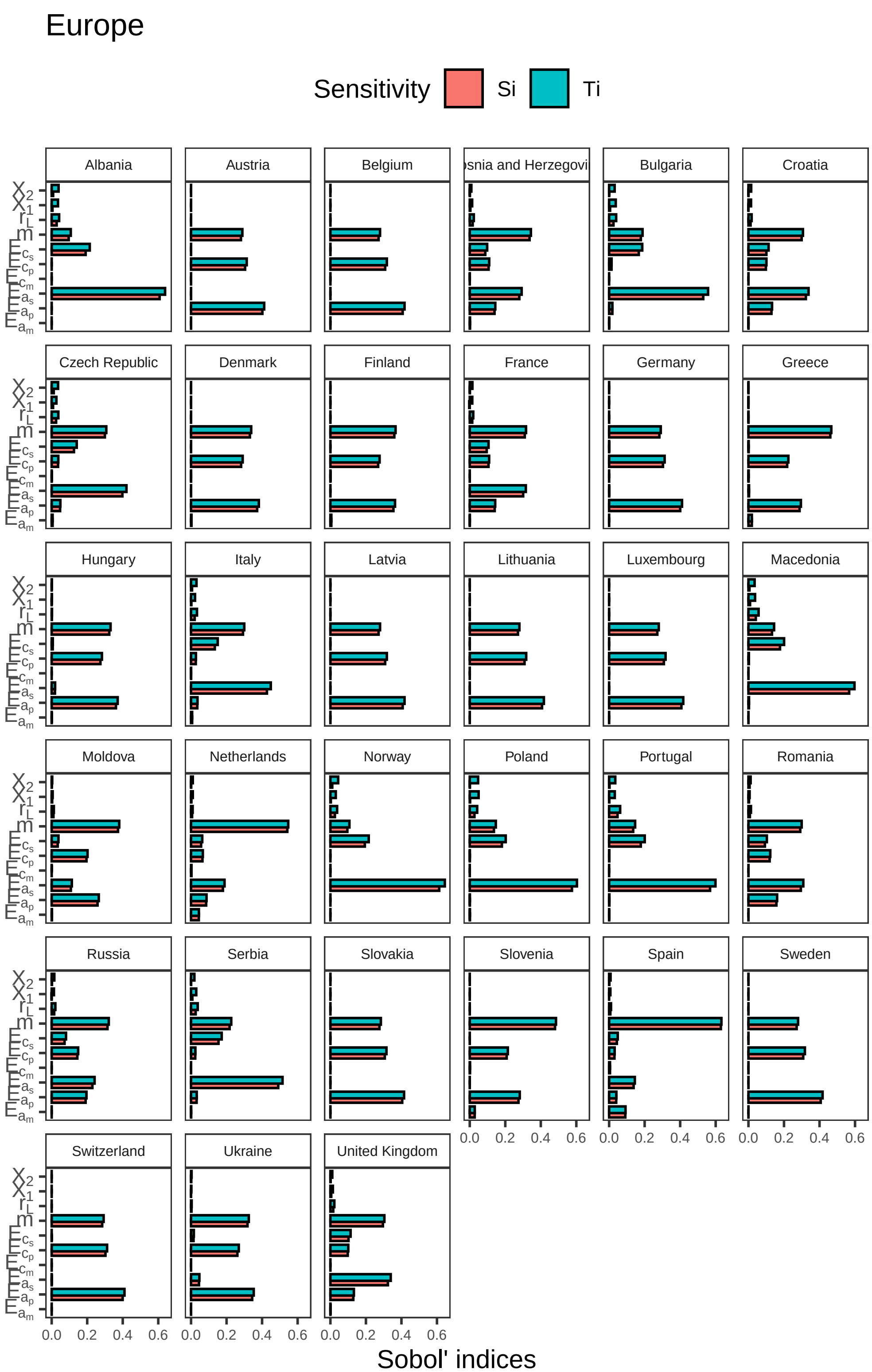
```
##
## [[2]]
```


Americas
Sensitivity
Si
Ti
Argentina
Belize
Bolivia
Brazil
Canada
Chile
Colombia
Costa Rica
Cuba
Dominican Republic
Ecuador
El Salvador
Guatemala
Guyana
Haiti
Honduras
Jamaica
Mexico
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
Suriname
United States
Uruguay
Venezuela
X_2
X_1
r_L
m
E_{c_s}
E_{c_p}
E_{c_m}
E_{a_s}
E_{a_p}
E_{a_m}
0.0 0.2 0.4 0.6
Sobol' indices

```
##
## [[3]]
```


Asia
Sensitivity
Si
Ti
Afghanistan
Armenia
Azerbaijan
Bangladesh
Bhutan
Brunei
Cambodia
China
Cyprus
Georgia
India
Indonesia
Iran
Iraq
Israel
Japan
Jordan
Kazakhstan
Kuwait
Kyrgyzstan
Laos
Lebanon
Malaysia
Mongolia
Nepal
North Korea
Oman
Pakistan
Philippines
Qatar
Saudi Arabia
South Korea
Sri Lanka
Syria
Tajikistan
Thailand
Turkey
Turkmenistan
ited Arab Emirat
Uzbekistan
Vietnam
Yemen
0.0 0.2 0.4 0.6
Sobol' indices

```
##
## [[4]]
```




```
# SESSION INFORMATION --------------------------------------------------------------

sessionInfo()
```

```
## R version 4.0.3 (2020-10-10)
```

```
## Platform: x86_64-apple-darwin17.0 (64-bit)
## Running under: macOS Big Sur 10.16
##
## Matrix products: default
## BLAS:   /Library/Frameworks/R.framework/Versions/4.0/Resources/lib/libRblas.dylib
## LAPACK: /Library/Frameworks/R.framework/Versions/4.0/Resources/lib/libRlapack.dylib
##
## locale:
## [1] en_US.UTF-8/en_US.UTF-8/en_US.UTF-8/C/en_US.UTF-8/en_US.UTF-8
##
## attached base packages:
## [1] parallel  stats     graphics  grDevices utils     datasets  methods
## [8] base
##
## other attached packages:
##  [1] checkpoint_1.0.0  benchmarkme_1.0.7 ncdf4_1.17        rworldmap_1.3-6
##  [5] sp_1.4-5          overlapping_1.6   testthat_3.0.4    scales_1.1.1
##  [9] ggridges_0.5.3    countrycode_1.3.0 doParallel_1.0.16 iterators_1.0.13
## [13] foreach_1.5.1     cowplot_1.1.1     wesanderson_0.3.6 sensobol_1.0.3
## [17] forcats_0.5.1     stringr_1.4.0     dplyr_1.0.7       purrr_0.3.4
## [21] readr_2.0.1       tidyr_1.1.3       tibble_3.1.3      ggplot2_3.3.5
## [25] tidyverse_1.3.1   data.table_1.14.0
##
## loaded via a namespace (and not attached):
##  [1] fs_1.5.0              lubridate_1.7.10      httr_1.4.2
##  [4] tools_4.0.3           backports_1.2.1       utf8_1.2.2
##  [7] R6_2.5.0              DBI_1.1.1             colorspace_2.0-2
## [10] withr_2.4.2           tidyselect_1.1.1      gridExtra_2.3
## [13] compiler_4.0.3        cli_3.0.1             rvest_1.0.1
## [16] xml2_1.3.2            digest_0.6.27         foreign_0.8-81
## [19] rmarkdown_2.10        benchmarkmeData_1.0.4 pkgconfig_2.0.3
## [22] htmltools_0.5.1.1     highr_0.9             dbplyr_2.1.1
## [25] maps_3.3.0            rlang_0.4.11          readxl_1.3.1
## [28] rstudioapi_0.13       farver_2.1.0          generics_0.1.0
## [31] tikzDevice_0.12.3.1   jsonlite_1.7.2        magrittr_2.0.1
## [34] dotCall64_1.0-1       Matrix_1.3-4          Rcpp_1.0.7
## [37] munsell_0.5.0         fansi_0.5.0           viridis_0.6.1
## [40] lifecycle_1.0.0       stringi_1.7.3         yaml_2.2.1
## [43] plyr_1.8.6            grid_4.0.3            maptools_1.1-1
## [46] crayon_1.4.1          lattice_0.20-44       haven_2.4.3
## [49] hms_1.1.0             knitr_1.33            pillar_1.6.2
## [52] codetools_0.2-18      reprex_2.0.1          glue_1.4.2
## [55] evaluate_0.14         modelr_0.1.8          vctrs_0.3.8
## [58] spam_2.7-0            tzdb_0.1.2            Rdpack_2.1.2
## [61] cellranger_1.1.0      gtable_0.3.0          assertthat_0.2.1
## [64] xfun_0.25             rbibutils_2.2.3       broom_0.7.9
## [67] filehash_2.4-2        viridisLite_0.4.0     fields_12.5
## [70] ellipsis_0.3.2
```

```r
## Return the machine CPU
cat("Machine:     "); print(get_cpu()$model_name)
```

```
## Machine:
```

```
## [1] "Intel(R) Core(TM) i9-9900K CPU @ 3.60GHz"
```

```r
## Return number of true cores
cat("Num cores:   "); print(detectCores(logical = FALSE))
```

```
## Num cores:
```

```
## [1] 8
```

```r
## Return number of threads
cat("Num threads: "); print(detectCores(logical = FALSE))
```

```
## Num threads:
```

```
## [1] 8
```