Global irrigation water demands biased by unreliable irrigation efficiencies

R code

Arnald Puy

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())
```

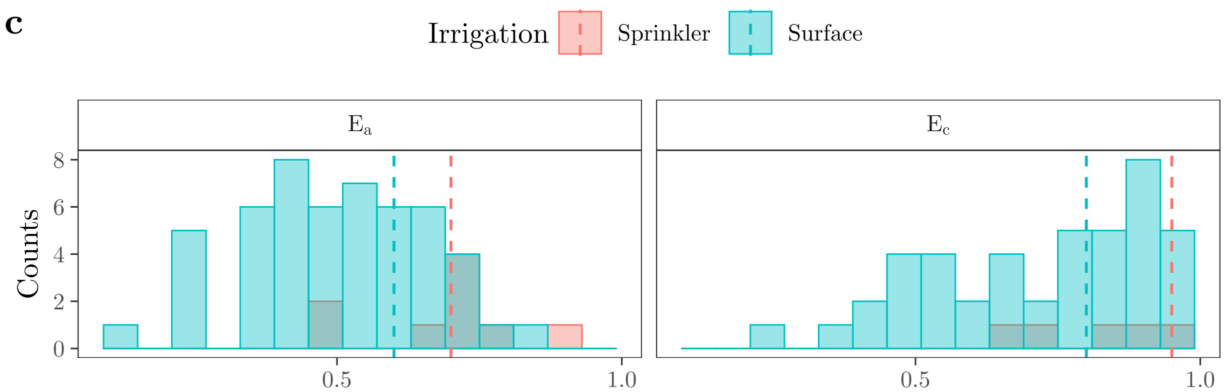
2 Read in data

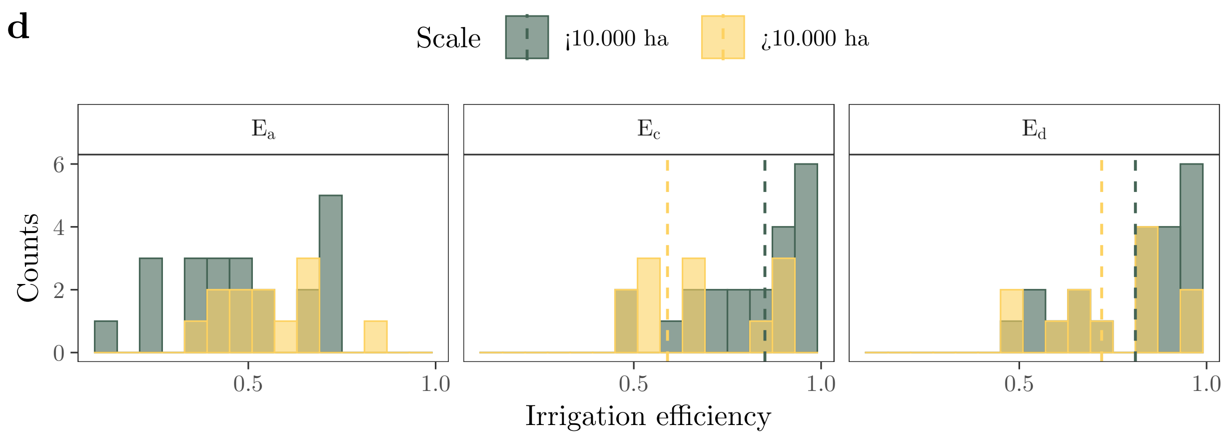
```
# READ IN DATA -------------------------------------------------------------------

# 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
```

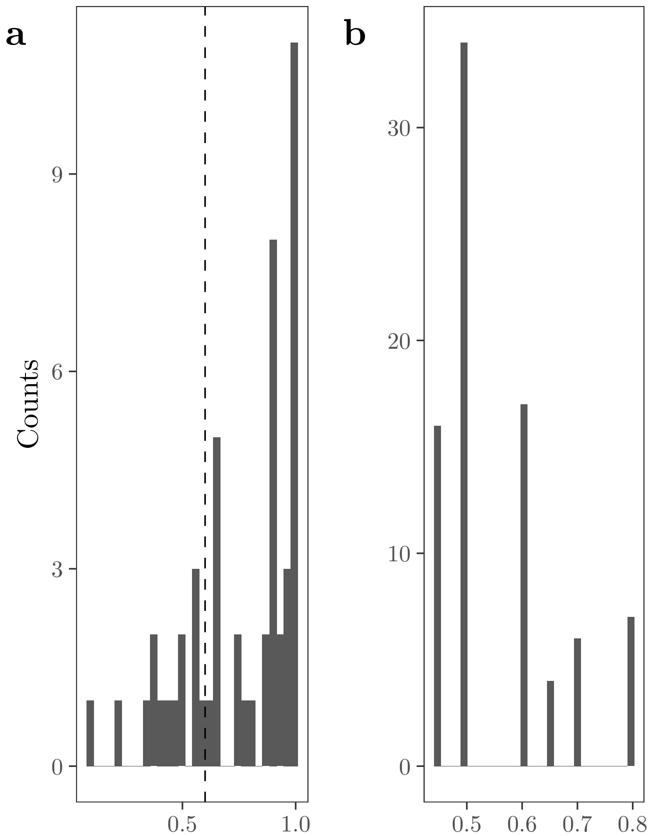




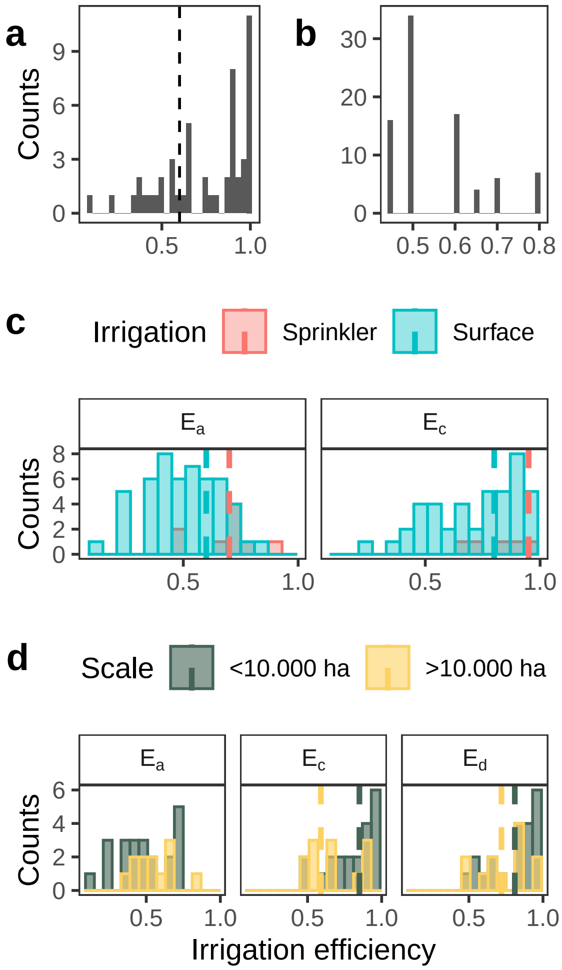

```
# PLOT USA AND AFRICA -------------------------------------------------------------

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`.
```

```
top
```




```
# 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,
```

```
  # 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 * (3 - 1 + 1)) + 1
)
```

3.3 Uncertainty in the proportion of large-scale irrigated areas

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

eff10 <- fread("efficiency_10.csv")
eff30 <- fread("efficiency_30.csv")
eff100 <- fread("efficiency_100.csv")

# CHECK WHICH COUNTRIES FROM ROHWER ET AL. ARE MISSING IN THE
# LARGE-SCALE IRRIGATED AREA DATASETS ----------------------------------------

countryDiff <- setdiff(rohwer$Country, eff100$Country)
countryMissing <- data.table(Country = rep(countryDiff, each = 12),
                             X1 = rep(1:4, each = 3),
                             X2 = rep(1:3, times = 4),
                             Proportion_large = 0)

# ARRANGE DATASETS ---------------------------------------------------------------

largescale.dt <- rbind(eff10, eff30, eff100) %>%
  melt(., measure.vars = 3:6, variable.name = "X1",
       value.name = "Proportion_large") %>%
  .[, Code:= NULL] %>%
  setcolorder(., c("Country", "X1", "X2", "Proportion_large")) %>%
```

```
  .[, X1:= ifelse(X1 == "FAO-GMIA", 1,
                  ifelse(X1 == "GRIPC", 2,
                         ifelse(X1 == "GIAM", 3, 4)))] %>%
  .[, X2:= ifelse(X2 == 1000, 1,
                  ifelse(X2 == 3000, 2, 3))] %>%
  # Add missing countries
  rbind(., countryMissing) %>%
  merge(rohwer[, .(Country, IFT)], ., by = "Country", all.x = TRUE) %>%
  .[, index:= paste(Country, X1, X2, sep = ".")]

largescale.dt[is.na(largescale.dt)] <- 0

# SETKEY ----------------------------------------------------------------------

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

3.4 Function to create sample matrix and transfrom to appropriate distributions

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

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
  out <- list(tmp$parameters, mat)
  names(out) <- c("parameters", "matrix")
  return(out)
}
```

3.5 Define the model

```
# 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 ----------------------------------------------------------------------

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

```
# 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

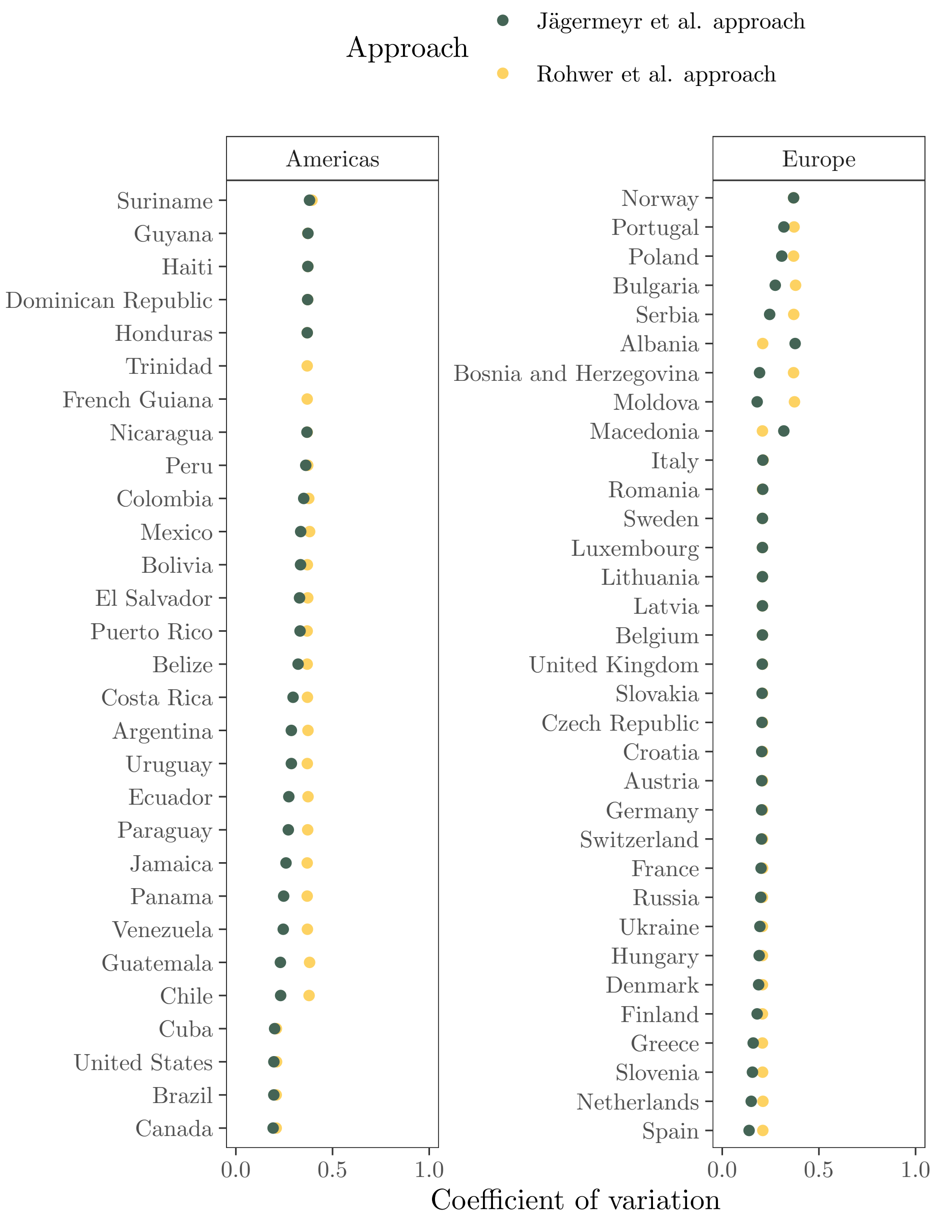
```
# CALCULATE COEFFICIENT OF VARIATION ---------------------------------------------

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

```r
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
Sudan
Egypt
Somalia
Nigeria
Burundi
Senegal
Eritrea
Mali
Madagascar
Gambia
Angola
Sierra Leone
Rwanda
Niger
Liberia
Guinea-Bissau
Equatorial Guinea
Djibouti
Central African Republic
Zaire
Western Sahara
Congo
Guinea
Ethiopia
Mauritania
Uganda
Chad
Morocco
Togo
Ghana
Cameroon
Tanzania
Gabon
Kenya
Lesotho
Algeria
Libya
Burkina Faso
Zambia
Swaziland
Tunisia
Ivory Coast
Mozambique
Benin
Malawi
Zimbabwe
Namibia
Botswana
South Africa
Pakistan
Uzbekistan
Bangladesh
Turkmenistan
India
Nepal
Vietnam
Burma
Tajikistan
Thailand
North Korea
South Korea
Kyrgyzstan
China
Philippines
Indonesia
Yemen
Cambodia
Laos
Bhutan
Afghanistan
Malaysia
Armenia
Iran
Georgia
Turkey
Japan
Syria
Azerbaijan
Iraq
Sri Lanka
Mongolia
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 0.4639176
##   2:      Asia   United Arab Emirates 0.4854683
```

```
##  3:     Asia                 Israel 0.4944147
##  4:     Asia                 Jordan 0.5042251
##  5:   Africa                Tunisia 0.5706087
##  6:     Asia           Saudi Arabia 0.5707274
##  7:   Europe                  Italy 0.5721363
##  8:   Africa              Swaziland 0.5726990
##  9: Americas          United States 0.5775350
## 10:   Europe            Netherlands 0.5782524
## 11: Americas                   Cuba 0.5818560
## 12:   Africa             Mozambique 0.5822536
## 13: Americas                 Brazil 0.5855978
## 14:   Africa                  Benin 0.5856878
## 15:   Africa                Namibia 0.5856878
## 16:   Africa               Zimbabwe 0.5856878
## 17:     Asia                Lebanon 0.5864389
## 18:   Europe                 France 0.5869800
## 19:   Africa           South Africa 0.5876042
## 20:   Africa                 Zambia 0.5890368
## 21:     Asia             Kazakhstan 0.5894648
## 22:   Africa            Ivory Coast 0.5903014
## 23:     Asia                 Brunei 0.5922976
## 24: Americas                 Canada 0.5944970
## 25:   Europe                  Spain 0.5984780
## 26:     Asia                 Kuwait 0.5998517
## 27:   Europe                Austria 0.6014893
## 28:   Europe                Belgium 0.6014893
## 29:     <NA>               Byelarus 0.6014893
## 30:   Europe                Denmark 0.6014893
## 31:   Europe                Finland 0.6014893
## 32:   Europe                Germany 0.6014893
## 33:   Europe                 Greece 0.6014893
## 34:   Europe                Hungary 0.6014893
## 35:   Europe                 Latvia 0.6014893
## 36:   Europe              Lithuania 0.6014893
## 37:   Europe             Luxembourg 0.6014893
## 38:   Africa                 Malawi 0.6014893
## 39:   Europe               Slovakia 0.6014893
## 40:   Europe                 Sweden 0.6014893
## 41:   Europe            Switzerland 0.6014893
## 42:   Africa               Botswana 0.6071124
## 43:   Europe                Ukraine 0.6122925
## 44:     Asia                  Qatar 0.6222104
## 45:   Europe         Czech Republic 0.6394465
## 46:   Europe                Croatia 0.6449088
## 47:   Europe                 Russia 0.6468832
## 48:   Europe         United Kingdom 0.6527024
## 49:   Europe               Slovenia 0.6529393
## 50:   Europe                Romania 0.6658015
```

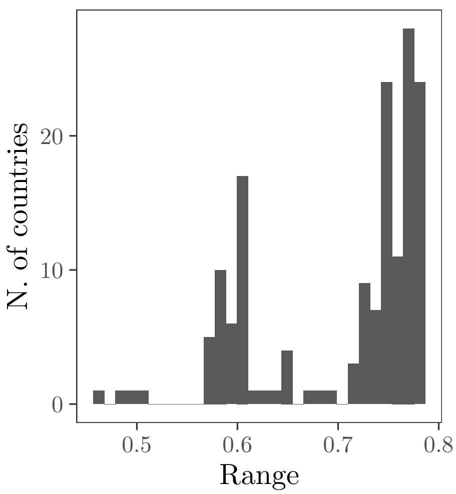
```
## 51:   Africa            Burkina Faso 0.6810580
## 52:   Africa                   Libya 0.6956438
## 53:     Asia              Azerbaijan 0.7146797
## 54:     Asia                   Syria 0.7165713
## 55:   Africa                 Algeria 0.7176049
## 56:     Asia                    Iraq 0.7217608
## 57:   Africa                 Morocco 0.7219235
## 58:  Oceania             New Zealand 0.7243644
## 59:     Asia                  Turkey 0.7249771
## 60:     Asia                 Armenia 0.7257428
## 61:  Oceania               Australia 0.7277279
## 62:   Africa                   Egypt 0.7287327
## 63: Americas                  Mexico 0.7295769
## 64:     Asia                   China 0.7310074
## 65:     Asia                    Iran 0.7320971
## 66: Americas                   Chile 0.7341855
## 67:     Asia                   India 0.7368912
## 68:     Asia                   Japan 0.7370818
## 69:   Europe                Bulgaria 0.7393857
## 70:     Asia                   Burma 0.7407613
## 71:     Asia             Afghanistan 0.7408257
## 72:     Asia             Philippines 0.7431090
## 73: Americas               Argentina 0.7460277
## 74:     Asia            Turkmenistan 0.7470244
## 75:     Asia                 Vietnam 0.7474112
## 76:     Asia                Pakistan 0.7475370
## 77: Americas                 Ecuador 0.7475424
## 78:   Europe               Macedonia 0.7477843
## 79:     Asia             North Korea 0.7482417
## 80: Americas                    Peru 0.7485998
## 81:     Asia              Uzbekistan 0.7486592
## 82:   Europe                 Moldova 0.7488747
## 83:   Africa                    Chad 0.7498686
## 84: Americas                Paraguay 0.7498686
## 85: Americas                 Uruguay 0.7498686
## 86:   Africa                   Sudan 0.7498884
## 87:     Asia                Malaysia 0.7503642
## 88:   Europe                Portugal 0.7505188
## 89:     Asia                Thailand 0.7505896
## 90: Americas                 Bolivia 0.7506488
## 91:     Asia              Bangladesh 0.7508831
## 92: Americas               Venezuela 0.7512531
## 93:     Asia               Sri Lanka 0.7513038
## 94:     Asia                   Nepal 0.7520751
## 95:   Africa                Cameroon 0.7527058
## 96:     Asia              Kyrgyzstan 0.7546852
## 97:     Asia               Indonesia 0.7566068
## 98: Americas                  Guyana 0.7568347
```

```
##  99:     Asia               Tajikistan 0.7569981
## 100:     Asia                  Georgia 0.7580011
## 101:     Asia              South Korea 0.7584425
## 102:     Asia                 Cambodia 0.7615212
## 103:   Africa                 Ethiopia 0.7628903
## 104:   Europe                  Albania 0.7632624
## 105:     Asia                    Yemen 0.7644014
## 106:   Africa                 Tanzania 0.7646283
## 107:   Africa                  Nigeria 0.7656979
## 108: Americas                    Haiti 0.7658826
## 109:     Asia                     Oman 0.7711095
## 110: Americas                   Belize 0.7728079
## 111:   Europe   Bosnia and Herzegovina 0.7728079
## 112:   Africa                    Congo 0.7728079
## 113: Americas            French Guiana 0.7728079
## 114:   Africa                    Gabon 0.7728079
## 115:   Africa                    Ghana 0.7728079
## 116: Americas                Guatemala 0.7728079
## 117:   Africa                   Guinea 0.7728079
## 118: Americas                  Jamaica 0.7728079
## 119:   Africa                  Lesotho 0.7728079
## 120:   Africa               Mauritania 0.7728079
## 121: Americas                   Panama 0.7728079
## 122:  Oceania         Papua New Guinea 0.7728079
## 123:   Europe                   Poland 0.7728079
## 124: Americas              Puerto Rico 0.7728079
## 125:   Africa                     Togo 0.7728079
## 126: Americas                 Trinidad 0.7728079
## 127:   Africa                   Uganda 0.7728079
## 128:   Africa           Western Sahara 0.7728079
## 129:   Africa                    Zaire 0.7728079
## 130:   Europe                   Serbia 0.7733555
## 131: Americas              El Salvador 0.7743265
## 132:   Africa                    Kenya 0.7743758
## 133: Americas               Costa Rica 0.7745177
## 134:     Asia                 Mongolia 0.7749708
## 135: Americas                 Colombia 0.7779004
## 136:   Africa                  Senegal 0.7793409
## 137: Americas                Nicaragua 0.7803721
## 138:   Africa               Madagascar 0.7806578
## 139:   Africa                     Mali 0.7808877
## 140:   Africa                   Angola 0.7814033
## 141:     Asia                   Bhutan 0.7814033
## 142:   Africa                  Burundi 0.7814033
## 143:   Africa Central African Republic 0.7814033
## 144:   Africa                 Djibouti 0.7814033
## 145: Americas       Dominican Republic 0.7814033
## 146:   Africa        Equatorial Guinea 0.7814033
```

```
## 147:    Africa                    Eritrea 0.7814033
## 148:    Africa                     Gambia 0.7814033
## 149:    Africa              Guinea-Bissau 0.7814033
## 150:  Americas                   Honduras 0.7814033
## 151:      Asia                       Laos 0.7814033
## 152:    Africa                    Liberia 0.7814033
## 153:    Africa                      Niger 0.7814033
## 154:    Europe                     Norway 0.7814033
## 155:    Africa                     Rwanda 0.7814033
## 156:    Africa               Sierra Leone 0.7814033
## 157:    Africa                    Somalia 0.7814033
## 158:  Americas                   Suriname 0.7830037
##       Continent                    Country     range
```

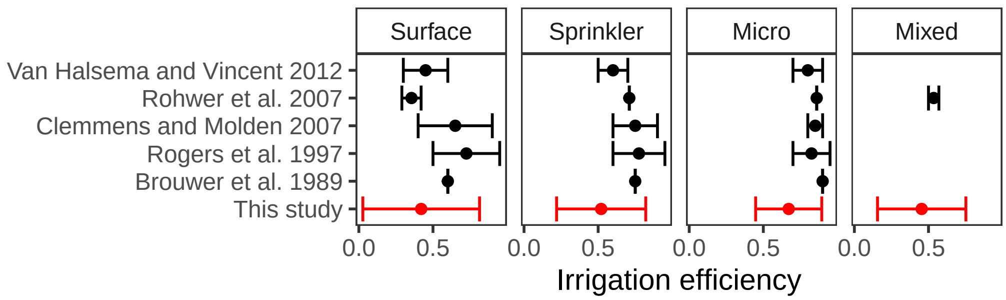
```r
ggplot(calc, aes(range)) +
  geom_histogram() +
  labs(x = "Range", y = "N. of countries") +
  theme_AP()
```

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




```r
# 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
##         0.3329115         0.5084454         0.5255184
##
## $Americas
## Surface-Mixed
##     0.5084078
##
## $Asia
## Surface-Micro Surface-Mixed   Micro-Mixed
##    0.05314604    0.42996793    0.07870342
##
## $Europe
## Surface-Sprinkler     Surface-Mixed   Sprinkler-Mixed
##         0.3372350         0.5362841         0.4917646
```

```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")]

ff[, .(median = median(V1)), Continent]
```

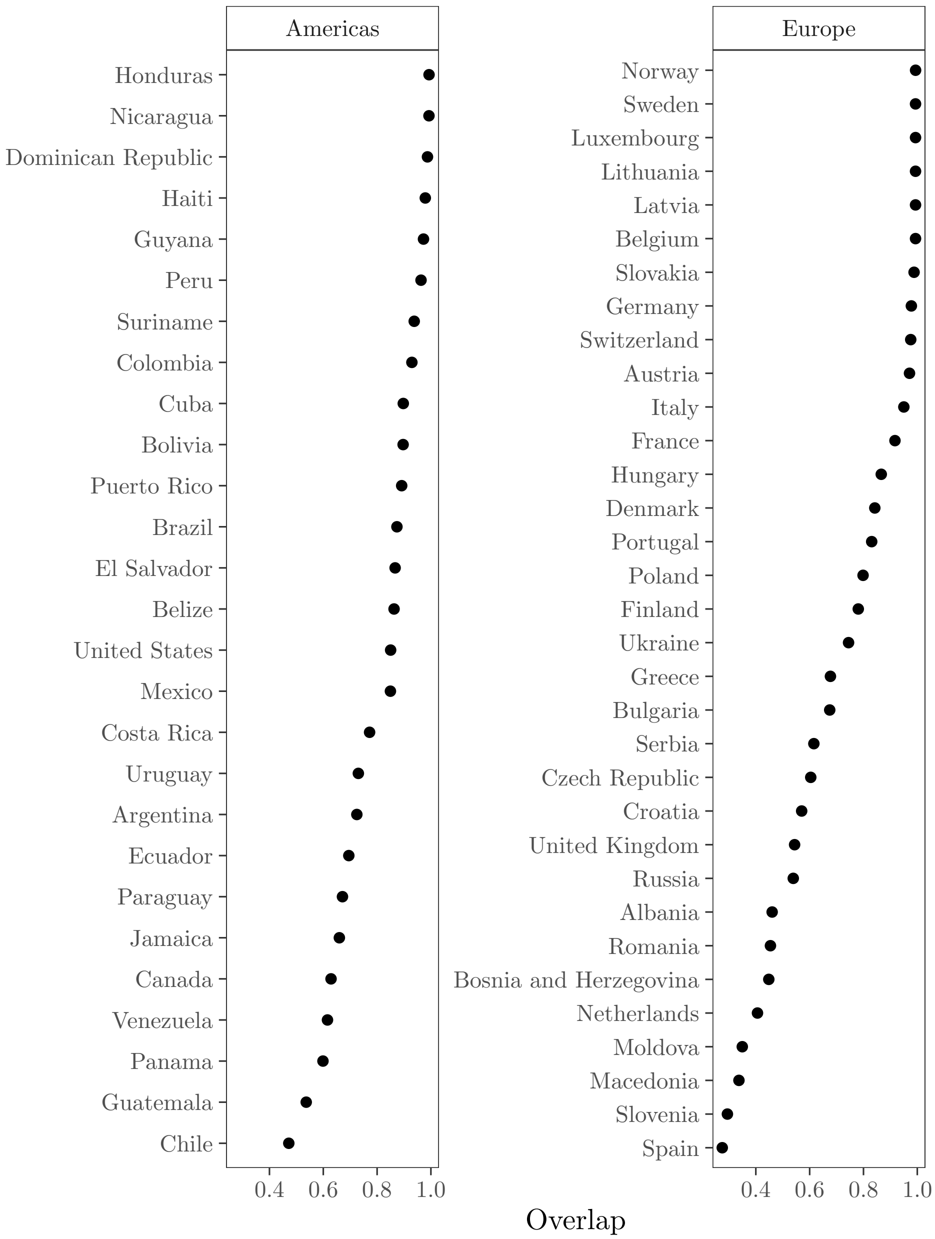
```
##    Continent    median
## 1:      Asia 0.9198489
## 2:    Europe 0.7806813
## 3:    Africa 0.9335912
## 4:  Americas 0.8630331
```

```r
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
```

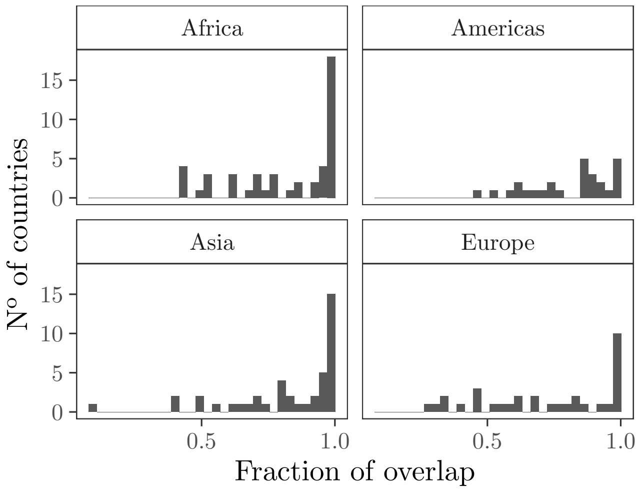
```
## [[1]]
```


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

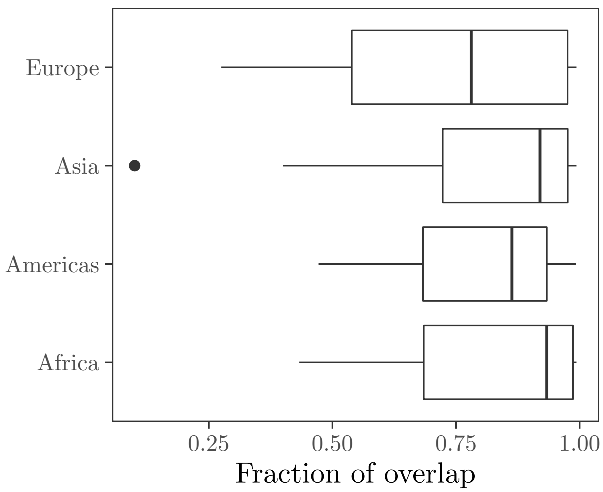
```
##
## [[2]]
```




```
# 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)]
```

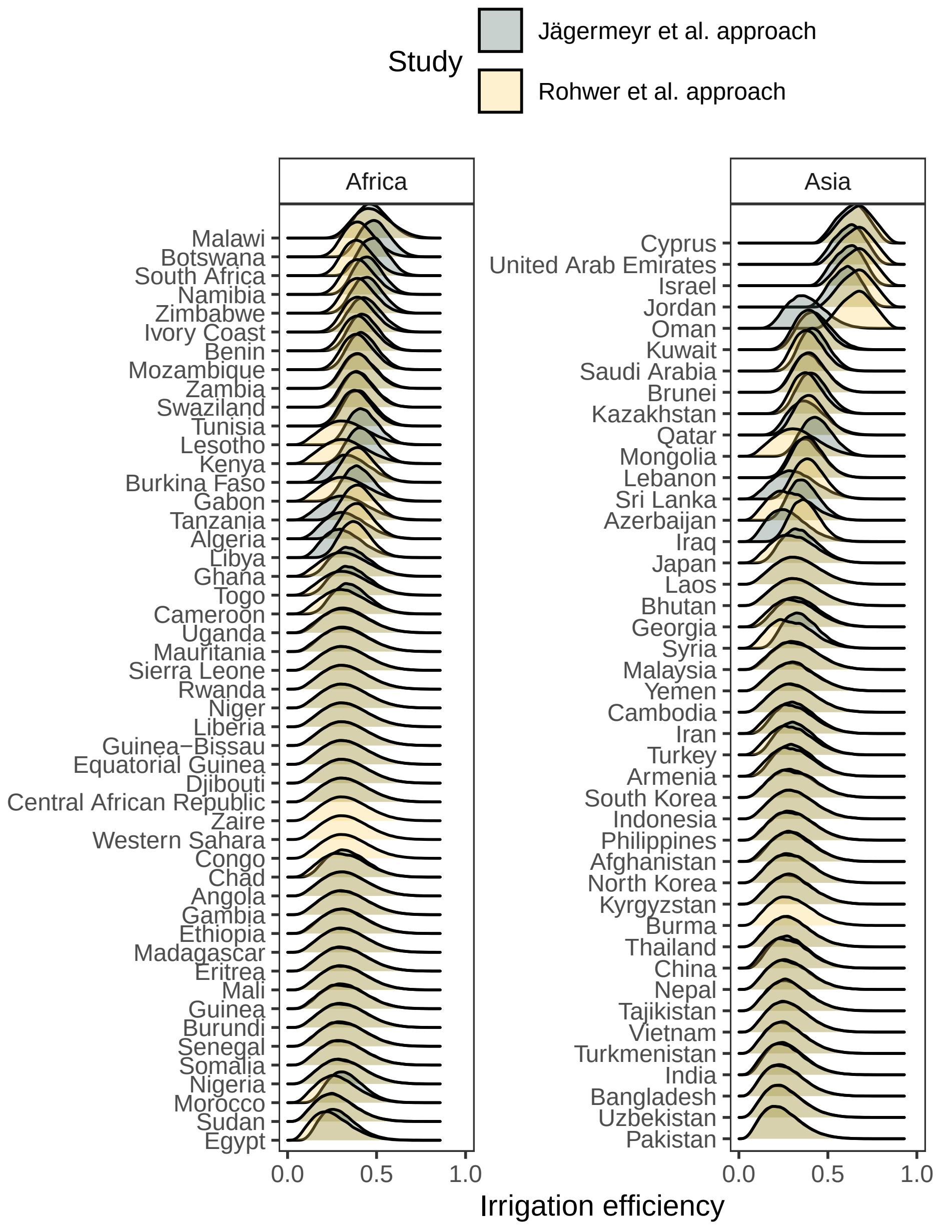
```
##      Country Surface_fraction Sprinkler_fraction Drip_fraction   IFT
## 1:      Oman            0.793              0.113         0.094 Micro
## 2: Slovenia            0.000              0.693         0.307 Mixed
## 3:     Spain            0.297              0.226         0.478 Mixed
```

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

gg <- list()
```

```r
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
```

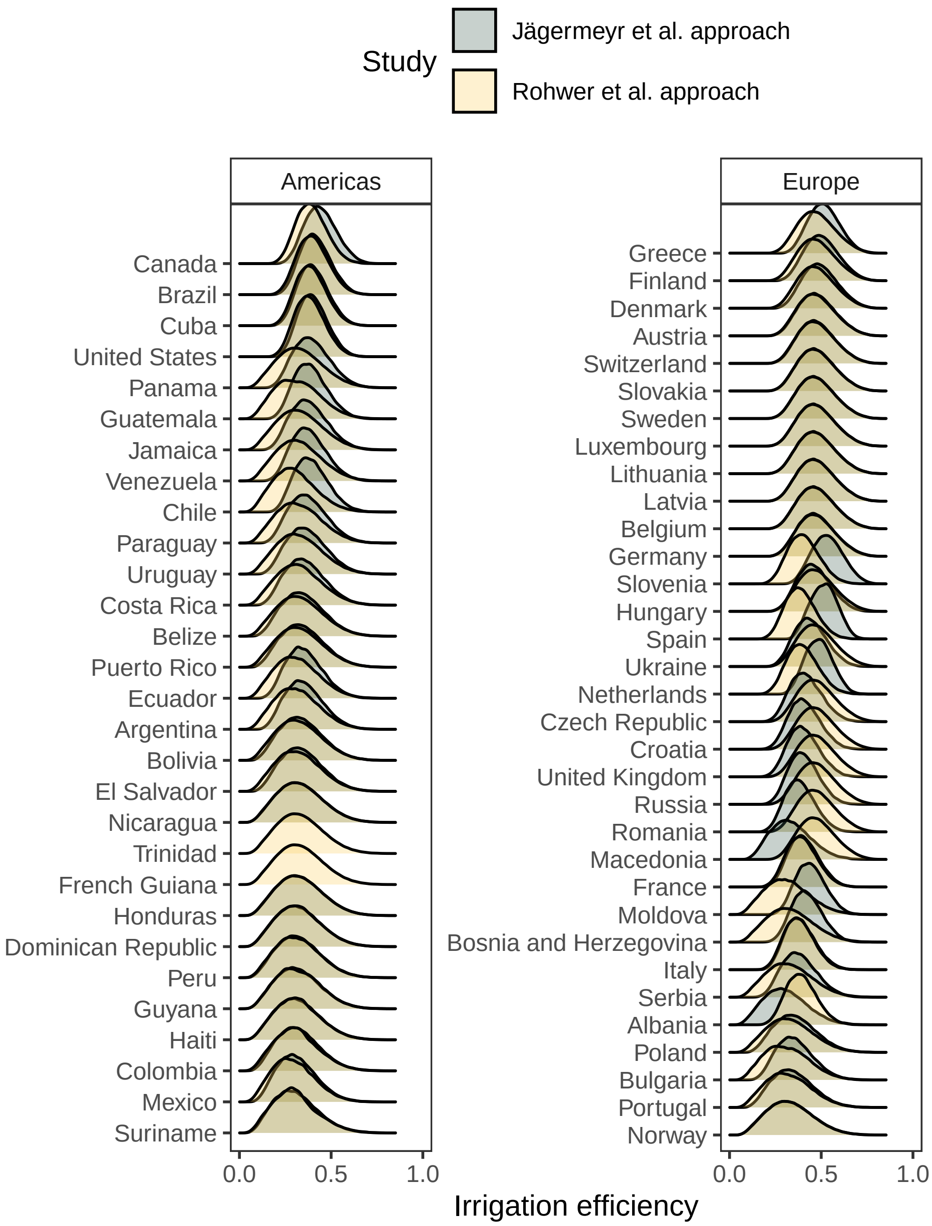
```
## [[1]]

## Picking joint bandwidth of 0.0121

## Picking joint bandwidth of 0.0118
```




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

```
## Picking joint bandwidth of 0.0123
```

```
## Picking joint bandwidth of 0.0109
```



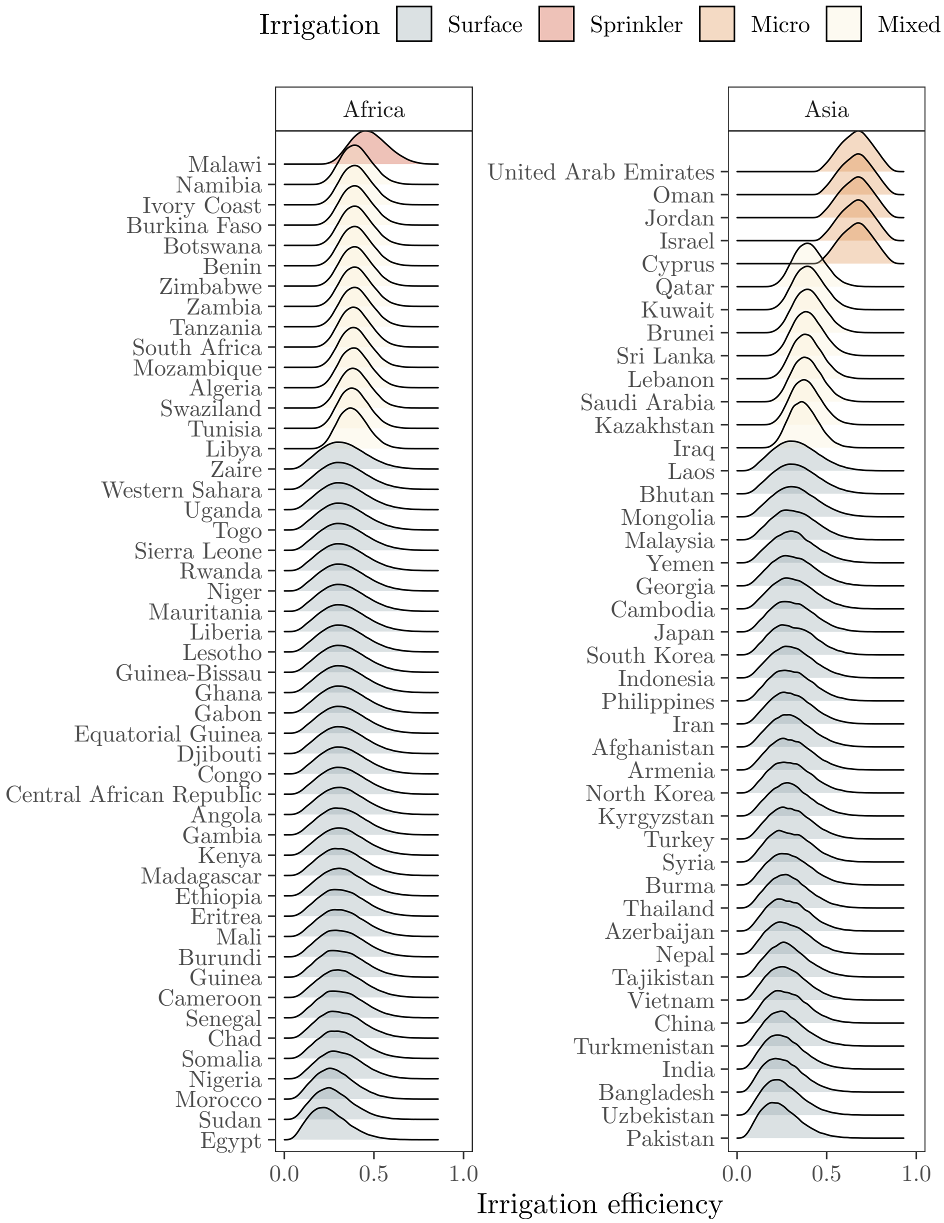

```
# PLOT UNCERTAINTY IN EACH IRRIGATION TECHNOLOGY ---------------------------------

gg <- list()

for(i in 1:length(list_continents)) {
  gg[[i]] <- uncertainty.dt[Approach == "Rohwer et al. 2007"][Continent %in% list_continents[[i
    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 0.0123
```

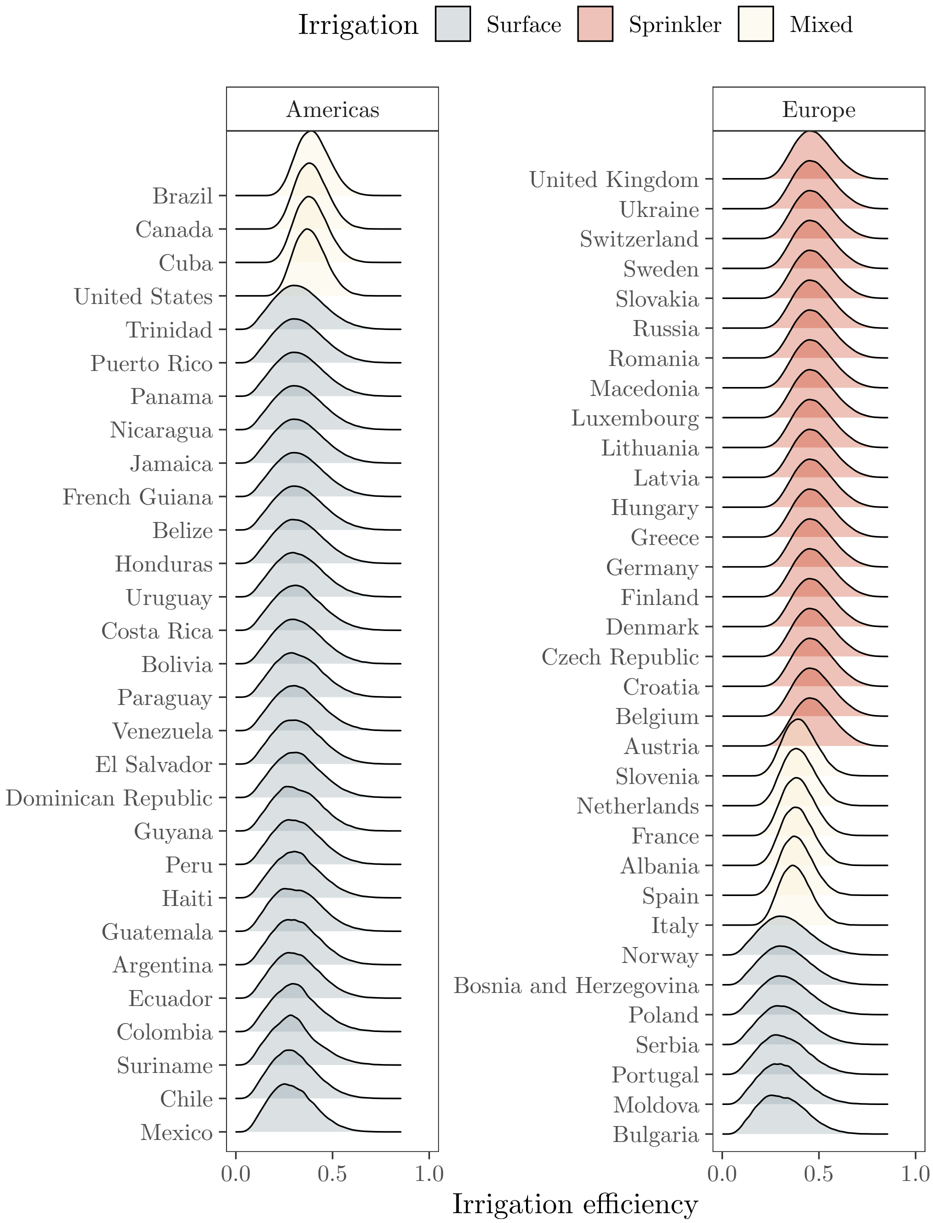
```
## Picking joint bandwidth of 0.0119
```




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

```
## Picking joint bandwidth of 0.0129
```

```
## Picking joint bandwidth of 0.0113
```



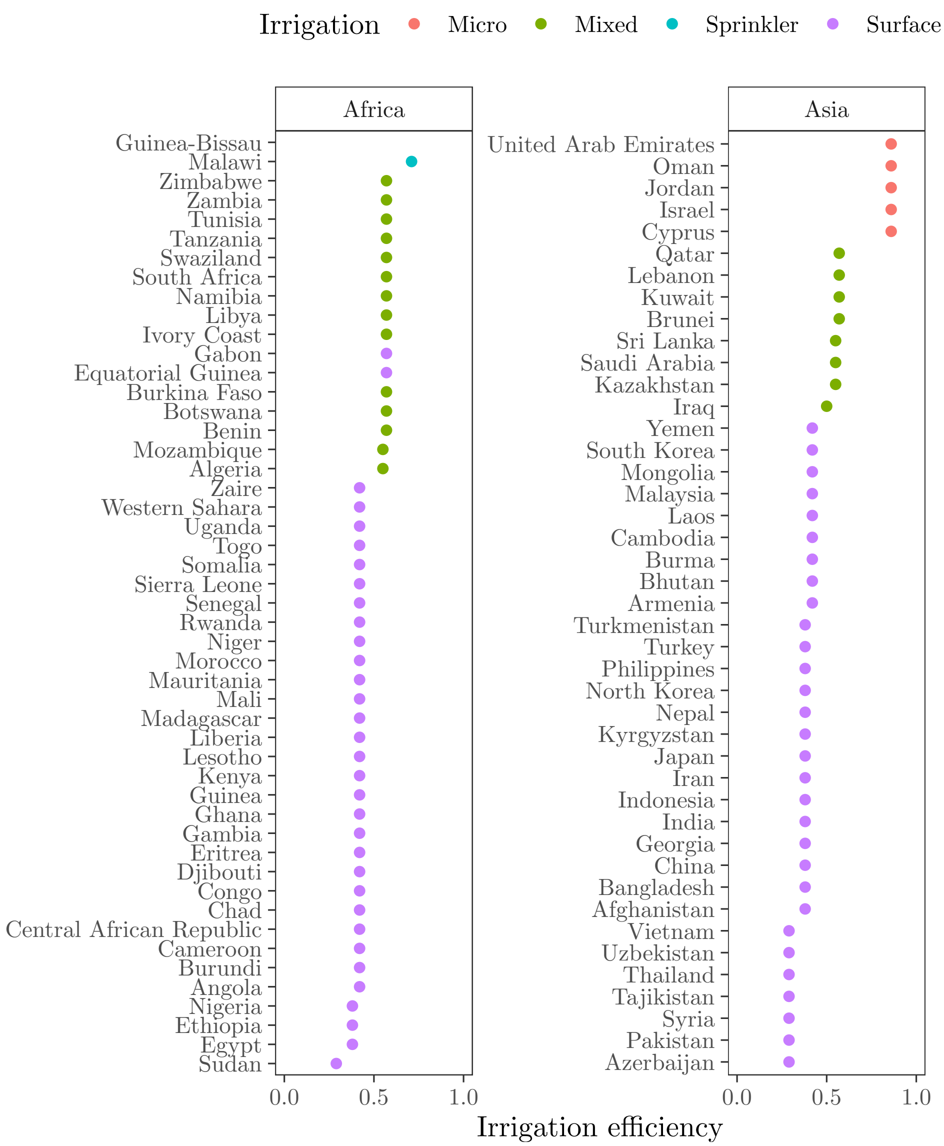

```
# PLOT ROHWER ET AL.'S IRRIGATION EFFICIENCY VALUES ------------------------------

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

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

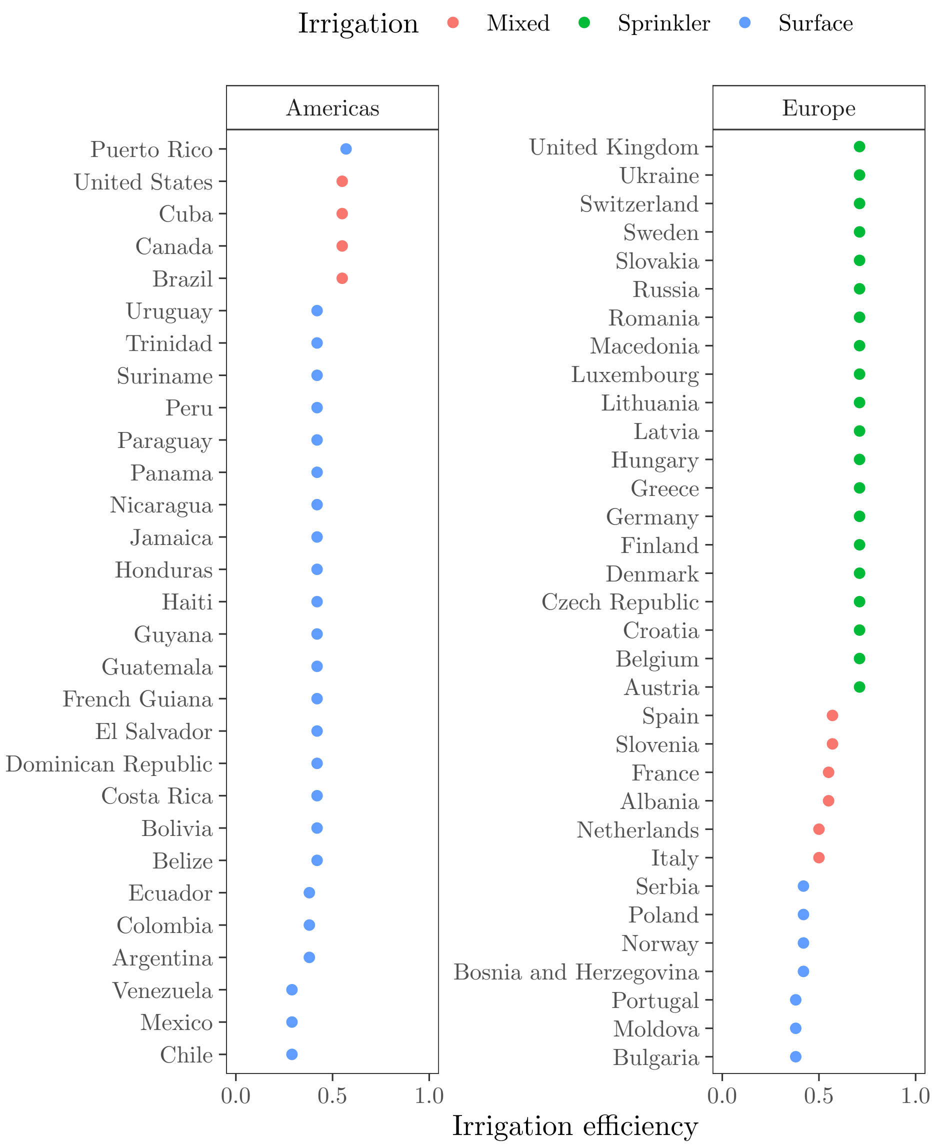
```
dd <- list()
for (i in 1:length(list_continents)) {
  dd[[i]] <- ggplot(rohwer[Continent %in% list_continents[[i]]],
                    aes(x = Ep, y = fct_reorder(Country, Ep), color = IFT)) +
    geom_point() +
    labs(x = "Irrigation efficiency", y = "") +
    scale_x_continuous(breaks = pretty_breaks(n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

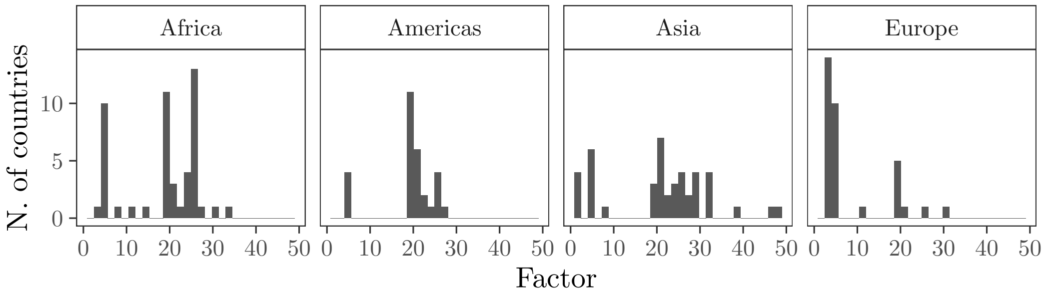



```
##
## [[2]]
```




```
# 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               28
##  4:      5                2
##  5:      7                1
##  6:      8                1
##  7:     11                2
##  8:     13                1
##  9:     19               29
## 10:     20               16
## 11:     21                4
## 12:     22                3
## 13:     23                3
## 14:     24                5
## 15:     25               20
## 16:     26                3
## 17:     27                3
## 18:     28                3
## 19:     29                1
## 20:     30                1
## 21:     31                3
## 22:     32                2
## 23:     33                1
## 24:     39                1
## 25:     47                1
## 26:     48                1
##     factor number.countries
```

4.4 Retrieve data from ISIMIP

```
# 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],
                             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)
}
```

```
# 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)
```

```
# 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]
```

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

names(isimip.dt) <- names.isimip

isimip.dt <- lapply(isimip.dt, function(x) rbindlist(x)) %>%
```

```r
  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")

isimip.quantiles <- isimip.dt[, .(quantile.low = quantile(Water.Withdrawn,
                                                           prob = 0.025, na.rm = TRUE),
                                  quantile.high = quantile(Water.Withdrawn,
                                                            prob = 0.975, na.rm = TRUE)),
                              .(Continent, Country)] %>%
  .[, Approach:= "GMs"]

isimip.dt.unc.efficiencies <- merge(efficiency.dt, isimip.dt,
                                    by = c("Country", "Continent"), all.x = TRUE,
                                    allow.cartesian = TRUE) %>%
  .[, Water.Withdrawn:= Water.Withdrawn / Ep] %>%
  .[, .(quantile.low = quantile(Water.Withdrawn, prob = 0.025, na.rm = TRUE),
    quantile.high = quantile(Water.Withdrawn, prob = 0.975, na.rm = TRUE)),
    .(Continent, Country)] %>%
  .[, Approach:= "GMs + uncertainty in irrigation efficiency"]
```

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",
```

```
  "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
)
```

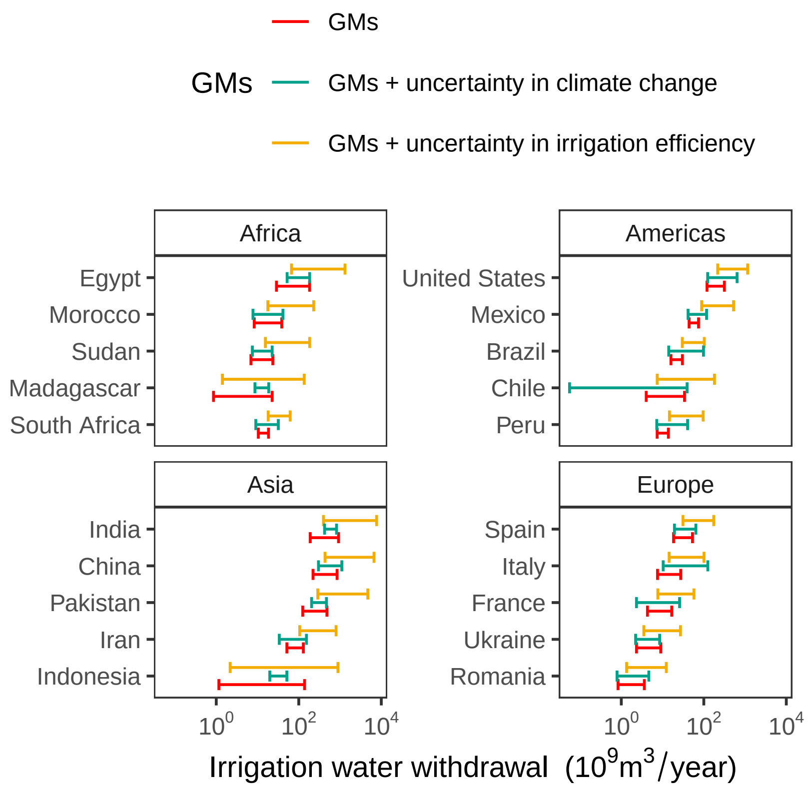
```
# ARRANGE DATASETS ---------------------------------------------------------------

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
# Check global IWW estimates per scenario and model
isimip.climate.dt[, .(total = sum(Water.Withdrawn, na.rm = TRUE)),
                  .(Model, `Climate scenario`)]
```

```
##          Model Climate scenario    total
##  1:   WaterGap               85 3485.197
##  2:   WaterGap               60 3402.798
##  3:   WaterGap               45 3386.301
##  4:   WaterGap               26 3408.670
##  5:      LPJmL               85 4737.365
##  6:      LPJmL               60 4946.130
##  7:      LPJmL               26 5132.723
##  8: PCR-GLOBWB               60 2363.518
##  9: PCR-GLOBWB               26 2205.154
## 10:        H08               85 3005.536
## 11:        H08               60 3036.963
## 12:        H08               26 3000.563
```

```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")

isimip.climate <- isimip.climate.dt[, .(quantile.low = quantile(Water.Withdrawn, prob = 0.025,
                                       quantile.high = quantile(Water.Withdrawn, prob = 0.975
                                    .(Continent, Country)] %>%
  .[, Approach:= "GMs + uncertainty in climate change"]

all.uncertainties <- rbind(isimip.quantiles,
                           isimip.dt.unc.efficiencies,
                           isimip.climate) %>%
  .[, mean:= (quantile.low + quantile.high) / 2] %>%
  na.omit()


# 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 = quantile.high,
                    ymax = quantile.low),
                position = position_dodge(0.7)) +
```

```r
  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))
```

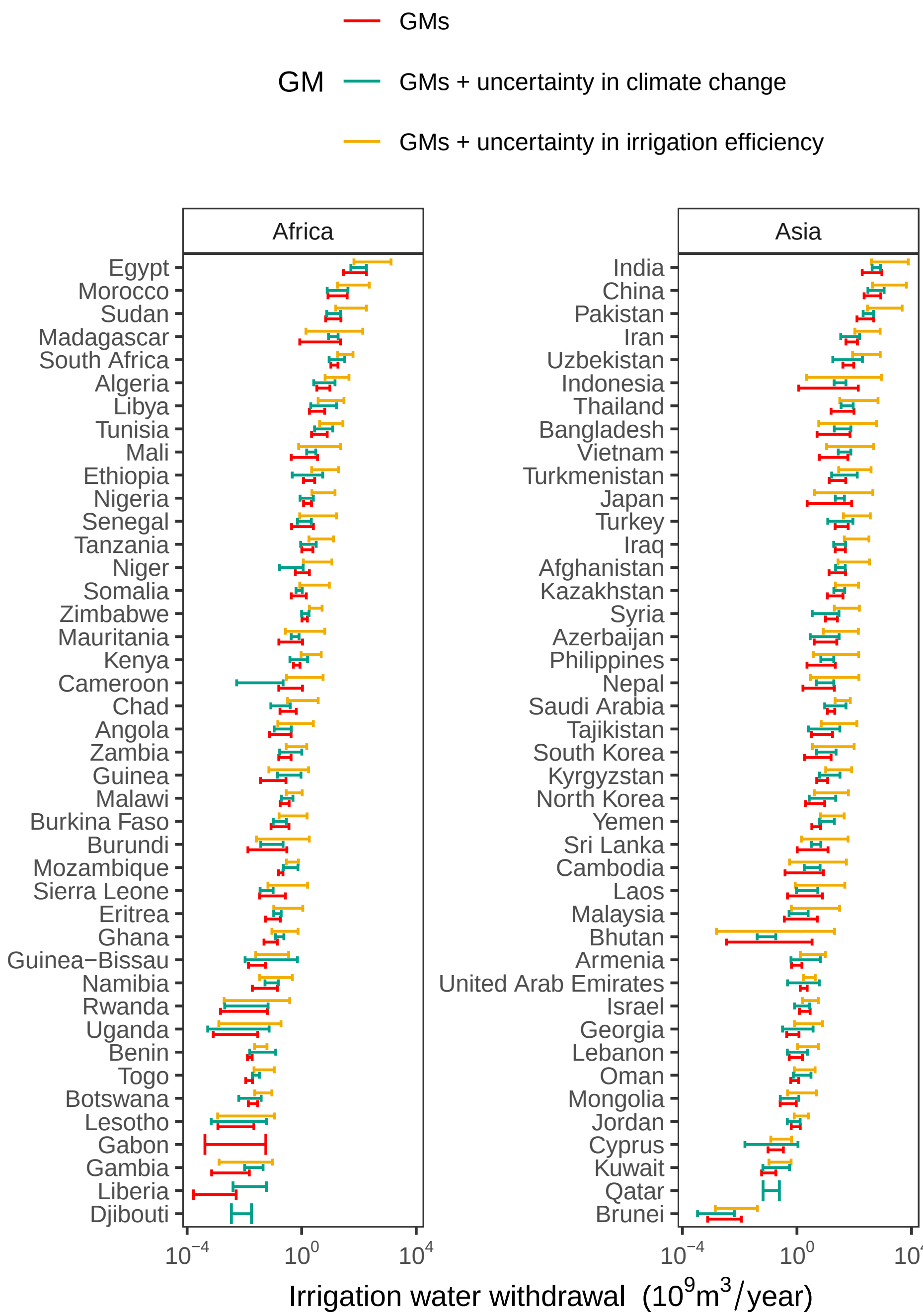



```r
# EXPORT -----------
fwrite(all.uncertainties, "all.uncertainties.csv")
```

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

vec1 <- all.uncertainties[Approach == "GMs", Country]
vec2 <- all.uncertainties[Approach == "GMs + uncertainty in climate change", Country]
vec3 <- all.uncertainties[Approach == "GMs + 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() %>%
```

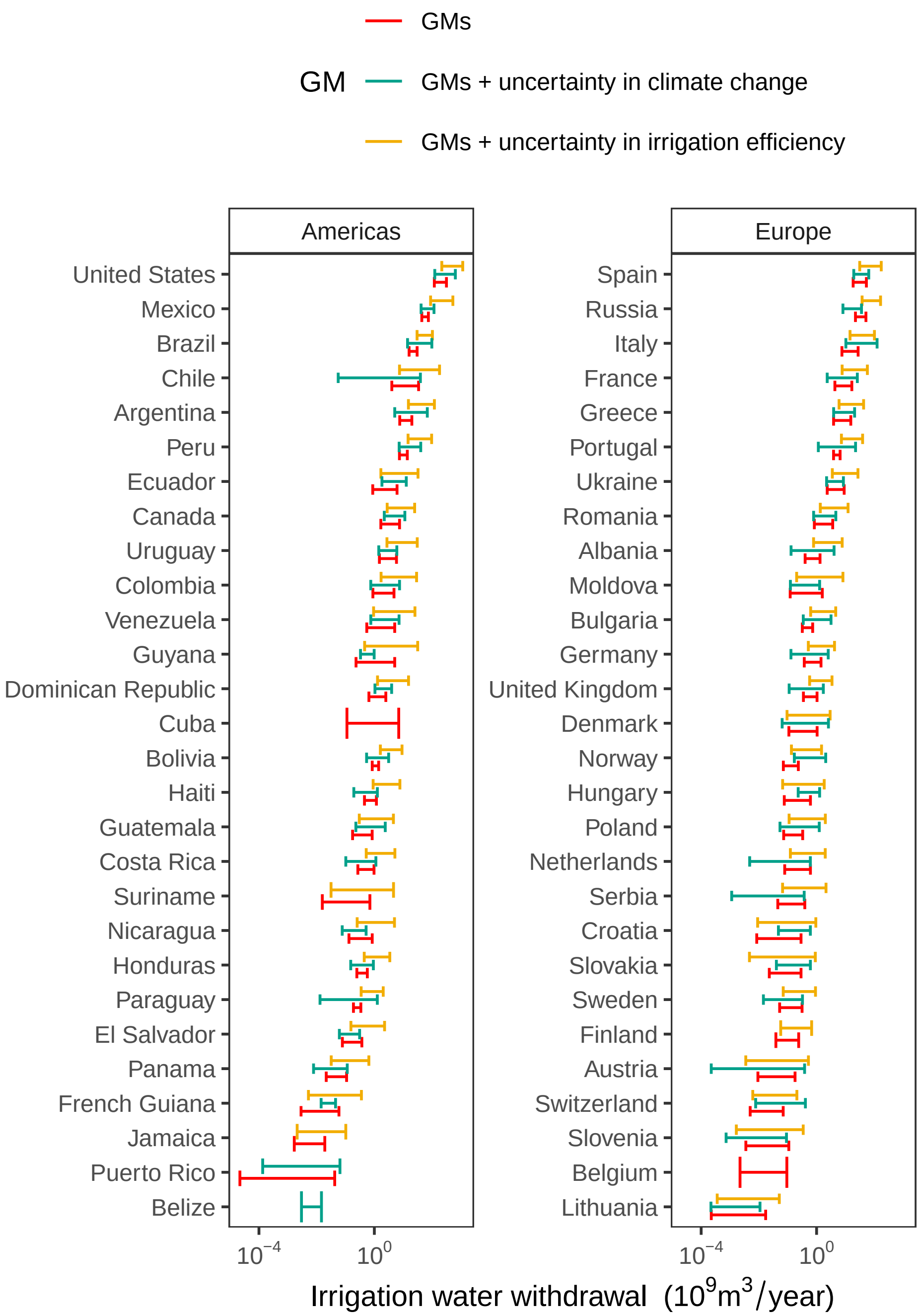
```
    .[Continent %in% list_continents[[i]]] %>%
    ggplot(., aes(reorder(Country, mean), mean, color = Approach)) +
    geom_errorbar(aes(ymin = quantile.high,
                      ymax = quantile.low),
                  position = position_dodge(0.7)) +
    scale_y_log10(breaks = trans_breaks("log10", 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]]
```



GM
GMs
GMs + uncertainty in climate change
GMs + uncertainty in irrigation efficiency
Africa
Asia
Egypt
Morocco
Sudan
Madagascar
South Africa
Algeria
Libya
Tunisia
Mali
Ethiopia
Nigeria
Senegal
Tanzania
Niger
Somalia
Zimbabwe
Mauritania
Kenya
Cameroon
Chad
Angola
Zambia
Guinea
Malawi
Burkina Faso
Burundi
Mozambique
Sierra Leone
Eritrea
Ghana
Guinea−Bissau
Namibia
Rwanda
Uganda
Benin
Togo
Botswana
Lesotho
Gabon
Gambia
Liberia
Djibouti
India
China
Pakistan
Iran
Uzbekistan
Indonesia
Thailand
Bangladesh
Vietnam
Turkmenistan
Japan
Turkey
Iraq
Afghanistan
Kazakhstan
Syria
Azerbaijan
Philippines
Nepal
Saudi Arabia
Tajikistan
South Korea
Kyrgyzstan
North Korea
Yemen
Sri Lanka
Cambodia
Laos
Malaysia
Bhutan
Armenia
United Arab Emirates
Israel
Georgia
Lebanon
Oman
Mongolia
Jordan
Cyprus
Kuwait
Qatar
Brunei
10^{-4}
10^{0}
10^{4}
Irrigation water withdrawal $(10^9 m^3/year)$


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




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

all.uncertainties <- all.uncertainties[, range:= quantile.high - quantile.low]

# Number of countries with larger uncertainties in irrigation efficiencies than climate change
# Number of countries with higher values in irrigation efficiency than climate change
measures <- c("range", "quantile.high")

out <- lapply(measures, function(measures)
  dcast(all.uncertainties, Continent + Country ~ Approach, value.var = measures) %>%
```

```
    .[, larger.uncertainties.efficiency:= ifelse(`GMs + uncertainty in irrigation efficiency` >
                                                   `GMs + uncertainty in climate change`, "Yes"
    .[, .(N = .N), larger.uncertainties.efficiency])

  out
```

```
## [[1]]
##    larger.uncertainties.efficiency   N
## 1:                             Yes 120
## 2:                              No   9
## 3:                            <NA>  53
##
## [[2]]
##    larger.uncertainties.efficiency   N
## 1:                             Yes 133
## 2:                              No  10
## 3:                            <NA>  39
```

```
  # Check countries
lapply(measures, function(measures)
  dcast(all.uncertainties, Continent + Country ~ Approach, value.var = measures) %>%
    .[, larger.uncertainties.efficiency:= ifelse(`GMs + uncertainty in irrigation efficiency` >
                                                   `GMs + uncertainty in climate change`, "Yes"
  .[larger.uncertainties.efficiency == "No"])
```

```
## [[1]]
##    Continent              Country         GMs
## 1:    Africa                Benin  0.00594274
## 2:    Africa        Guinea-Bissau  0.04111115
## 3:    Africa           Mozambique  0.06607217
## 4:  Americas               Brazil 14.33694644
## 5:      Asia               Cyprus  0.23571160
## 6:      Asia United Arab Emirates  0.96695120
## 7:    Europe                Italy 19.97188491
## 8:    Europe               Norway  0.16307885
## 9:    Europe          Switzerland  0.06470033
##    GMs + uncertainty in climate change
## 1:                           0.1085591
## 2:                           0.6994793
## 3:                           0.5120188
## 4:                          84.1270401
## 5:                           1.0711472
## 6:                           5.5771842
## 7:                         114.8287733
## 8:                           1.9073398
## 9:                           0.4028403
##    GMs + uncertainty in irrigation efficiency larger.uncertainties.efficiency
## 1:                                 0.03884875                              No
```

```
## 2:                                 0.32550630                             No
## 3:                                 0.47583202                             No
## 4:                                72.61218371                             No
## 5:                                 0.52161584                             No
## 6:                                 2.66299786                             No
## 7:                                86.78376652                             No
## 8:                                 1.35123554                             No
## 9:                                 0.20149893                             No
##
## [[2]]
##     Continent                  Country          GMs
##  1:    Africa                    Benin 1.870027e-02
##  2:    Africa Central African Republic 9.134051e-04
##  3:    Africa                 Djibouti 2.804800e-03
##  4:    Africa            Guinea-Bissau 5.495745e-02
##  5:    Africa                  Liberia 5.159788e-03
##  6:      Asia                   Cyprus 3.336008e-01
##  7:      Asia     United Arab Emirates 2.268531e+00
##  8:    Europe                    Italy 2.753716e+01
##  9:    Europe                   Norway 2.336077e-01
## 10:    Europe              Switzerland 6.969897e-02
##     GMs + uncertainty in climate change
##  1:                        1.239738e-01
##  2:                        5.607259e-03
##  3:                        1.761659e-02
##  4:                        7.100554e-01
##  5:                        5.888378e-02
##  6:                        1.086365e+00
##  7:                        6.044878e+00
##  8:                        1.251954e+02
##  9:                        2.076938e+00
## 10:                        4.105765e-01
##     GMs + uncertainty in irrigation efficiency larger.uncertainties.efficiency
##  1:                               6.135428e-02                             No
##  2:                               5.570572e-03                             No
##  3:                               1.710560e-02                             No
##  4:                               3.504841e-01                             No
##  5:                               3.532020e-02                             No
##  6:                               6.437018e-01                             No
##  7:                               4.349845e+00                             No
##  8:                               1.012278e+02                             No
##  9:                               1.485618e+00                             No
## 10:                               2.076458e-01                             No
```

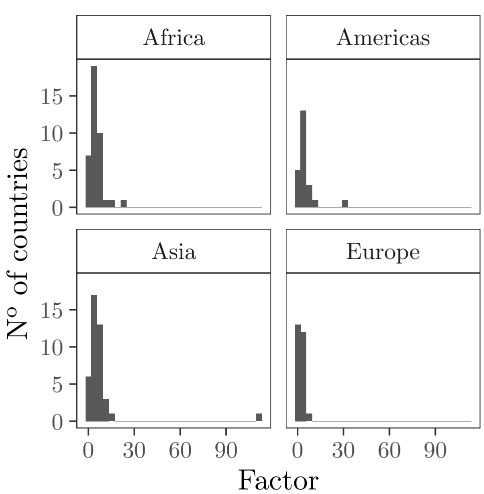
```
countries <- c("India", "Mexico", "Egypt", "Spain")
all.uncertainties[Country %in% countries] %>%
  .[order(Country)]
```

```
##     Continent Country quantile.low quantile.high
##  1:    Africa   Egypt     28.83614     182.79639
##  2:    Africa   Egypt     66.78065    1319.79828
##  3:    Africa   Egypt     52.19562     183.59849
##  4:      Asia   India    189.67967     921.47343
##  5:      Asia   India    397.13971    7700.72338
##  6:      Asia   India    422.37460     824.15135
##  7:  Americas  Mexico     44.07940      74.60312
##  8:  Americas  Mexico     88.79468     527.06169
##  9:  Americas  Mexico     41.60676     116.84276
## 10:    Europe   Spain     18.51645      53.25738
## 11:    Europe   Spain     31.32411     174.37175
## 12:    Europe   Spain     19.46677      64.26497
##                                  Approach       mean      range
##  1:                                   GMs  105.81626  153.96025
##  2: GMs + uncertainty in irrigation efficiency  693.28946 1253.01763
##  3:        GMs + uncertainty in climate change  117.89706  131.40287
##  4:                                   GMs  555.57655  731.79376
##  5: GMs + uncertainty in irrigation efficiency 4048.93155 7303.58367
##  6:        GMs + uncertainty in climate change  623.26298  401.77675
##  7:                                   GMs   59.34126   30.52372
##  8: GMs + uncertainty in irrigation efficiency  307.92818  438.26701
##  9:        GMs + uncertainty in climate change   79.22476   75.23600
## 10:                                   GMs   35.88691   34.74093
## 11: GMs + uncertainty in irrigation efficiency  102.84793  143.04764
## 12:        GMs + uncertainty in climate change   41.86587   44.79820
```

```r
# Plot differences in factors
all.uncertainties %>%
  na.omit() %>%
  dcast(., Continent + Country ~ Approach, value.var = "quantile.high") %>%
  .[, diff:= `GMs + uncertainty in irrigation efficiency` /
      `GMs + uncertainty in climate change`] %>%
  .[order(-diff)] %>%
  na.omit() %>%
  ggplot(., aes(diff)) +
  geom_histogram() +
  facet_wrap(~Continent) +
  labs(x = "Factor", y = "Nº of countries") +
  theme_AP()
```

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

## Warning in (function (texString, cex = 1, face = 1, engine =
## getOption("tikzDefaultEngine"), : Attempting to calculate the width of a Unicode
## stringusing the pdftex engine. This may fail! See the Unicodesection of ?
## tikzDevice for more information.

## Warning in (function (texString, cex = 1, face = 1, engine =
```

```
## getOption("tikzDefaultEngine"), : Attempting to calculate the width of a Unicode
## stringusing the pdftex engine. This may fail! See the Unicodesection of ?
## tikzDevice for more information.

## Warning in (function (texString, cex = 1, face = 1, engine =
## getOption("tikzDefaultEngine"), : Attempting to calculate the width of a Unicode
## stringusing the pdftex engine. This may fail! See the Unicodesection of ?
## tikzDevice for more information.

## Warning in (function (texString, cex = 1, face = 1, engine =
## getOption("tikzDefaultEngine"), : Attempting to calculate the width of a Unicode
## stringusing the pdftex engine. This may fail! See the Unicodesection of ?
## tikzDevice for more information.

## Warning in (function (texString, cex = 1, face = 1, engine =
## getOption("tikzDefaultEngine"), : Attempting to calculate the width of a Unicode
## stringusing the pdftex engine. This may fail! See the Unicodesection of ?
## tikzDevice for more information.

## Warning in (function (texString, cex = 1, face = 1, engine =
## getOption("tikzDefaultEngine"), : Attempting to calculate the width of a Unicode
## stringusing the pdftex engine. This may fail! See the Unicodesection of ?
## tikzDevice for more information.

## Warning in (function (texString, cex = 1, face = 1, engine =
## getOption("tikzDefaultEngine"), : Attempting to calculate the width of a Unicode
## stringusing the pdftex engine. This may fail! See the Unicodesection of ?
## tikzDevice for more information.

## Warning in (function (texString, cex = 1, face = 1, engine =
## getOption("tikzDefaultEngine"), : Attempting to calculate the width of a Unicode
## stringusing the pdftex engine. This may fail! See the Unicodesection of ?
## tikzDevice for more information.
```

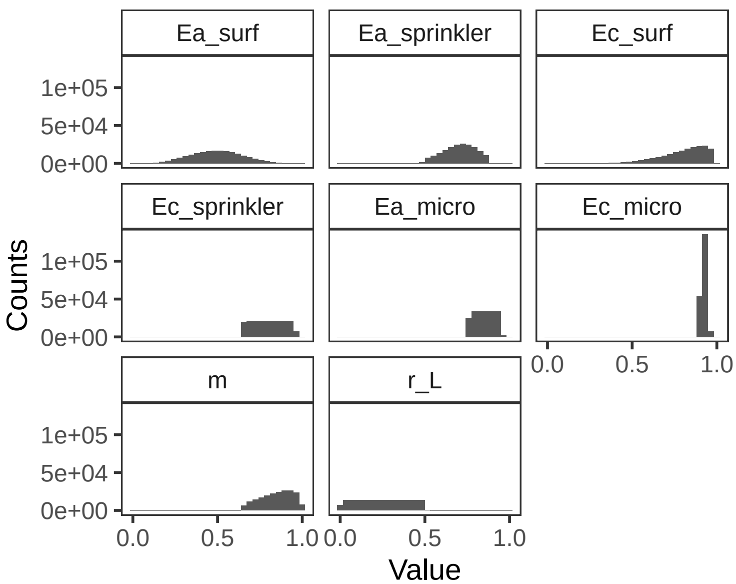


5 Sensitivity analysis

5.1 Probability distributions

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

mat <- data.table(full_sample_matrix(IFT = "Jager", Country = "Spain")$matrix)

melt(mat[, 1:8], measure.vars = colnames(mat)[-c(9,10)]) %>%
  ggplot(., aes(value)) +
  geom_histogram() +
  labs(x = "Value", y = "Counts") +
  scale_x_continuous(breaks = pretty_breaks(n = 3)) +
  facet_wrap(~variable, labeller = labeller(type = label_parsed)) +
  theme_AP()
```

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




```
# 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")]
```

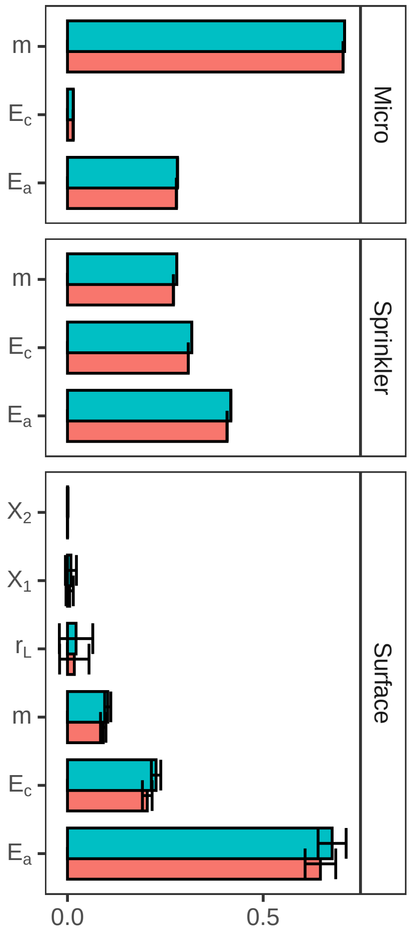
```
## Warning in countrycode_convert(sourcevar = sourcevar, origin = origin, destination = dest,
```

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

out <- list()
for(i in names(tmp.ift)) {
```

```
  out[[i]] <- ind[Country %in% tmp.ift[[i]][, Country]]
}
```

5.2 Sobol' indices

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

dt.indices <- rbindlist(out, idcol = "IFT") %>%
  .[!IFT == "Mixed"] %>%
  .[, .(mean = mean(original), sd = sd(original)), .(sensitivity, parameters, IFT)] %>%
  .[, parameters:= ifelse(parameters == "Ea_surf", "E[a]",
                         ifelse(parameters == "Ec_surf", "E[c]",
                                ifelse(parameters == "Ea_sprinkler", "E[a]",
                                       ifelse(parameters == "Ec_sprinkler", "E[c]",
                                              ifelse(parameters == "Ea_micro", "E[a]",
                                                     ifelse(parameters == "Ec_micro", "E[c]",
                                                            ifelse(parameters == "X1", "X[1]",
                                                                   ifelse(parameters == "X2", '
                                                                          ifelse(parameters ==

rohwer.indices <- ggplot(dt.indices, 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 = parse_format()) +
  scale_y_continuous(breaks = pretty_breaks(n = 2)) +
  scale_fill_discrete(name = "Sensitivity", labels = expression(S[i], T[i])) +
  labs(x = "", y = "") +
  coord_flip() +
  facet_grid(IFT~., space = "free_y", scale = "free_y") +
  theme_AP() +
  theme(legend.position = "none")

rohwer.indices
```



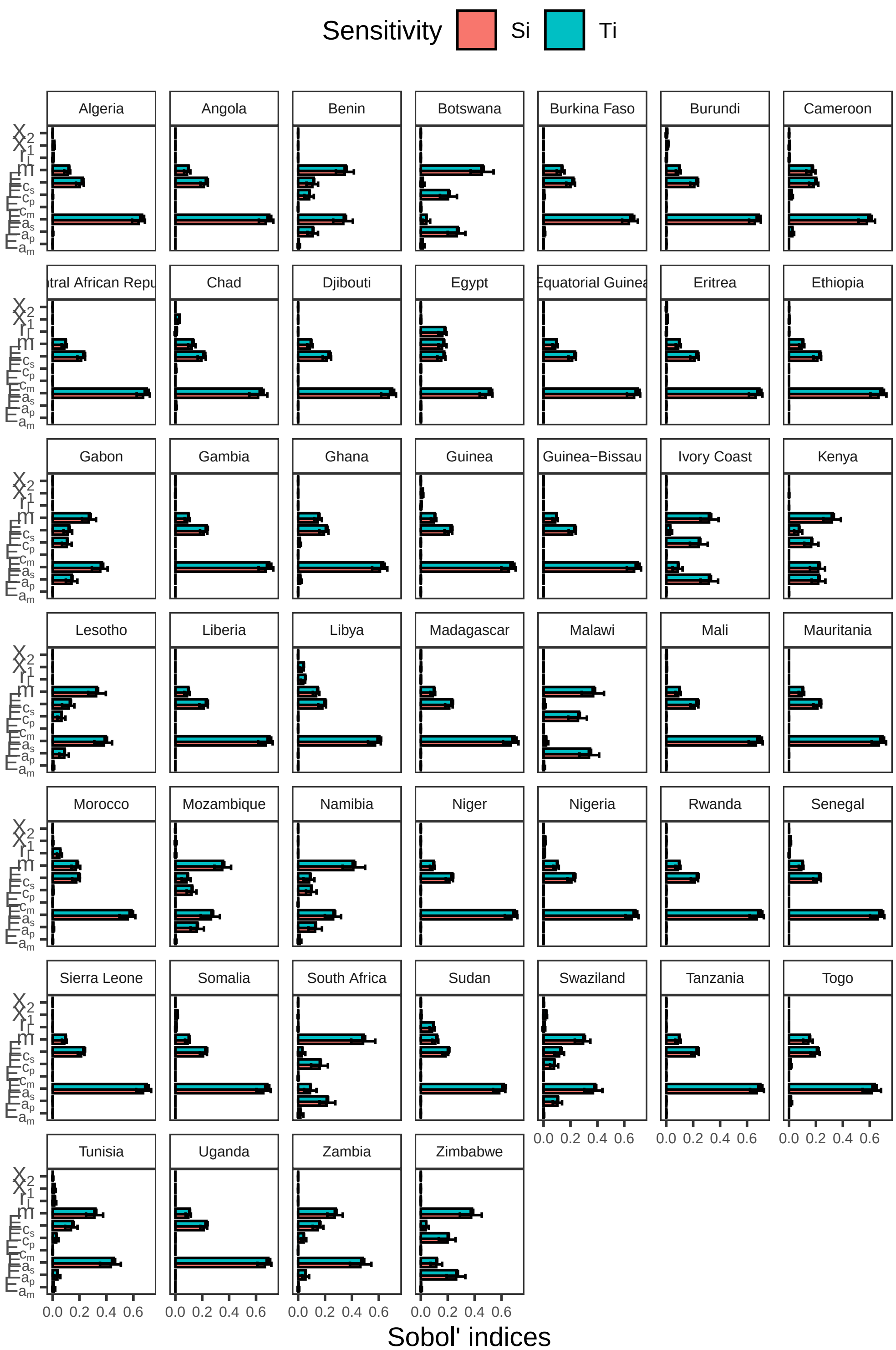

```
# EXTRACT SOBOL' INDICES FOR JAGER ----------------------------------------------

jager.tmp <- lapply(y[["Jägermeyr et al. 2015"]], function(x) x$indices$results)
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") +
    geom_errorbar(aes(ymin = low.ci, ymax = high.ci),
                  position = position_dodge(0.6)) +
    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]]
```

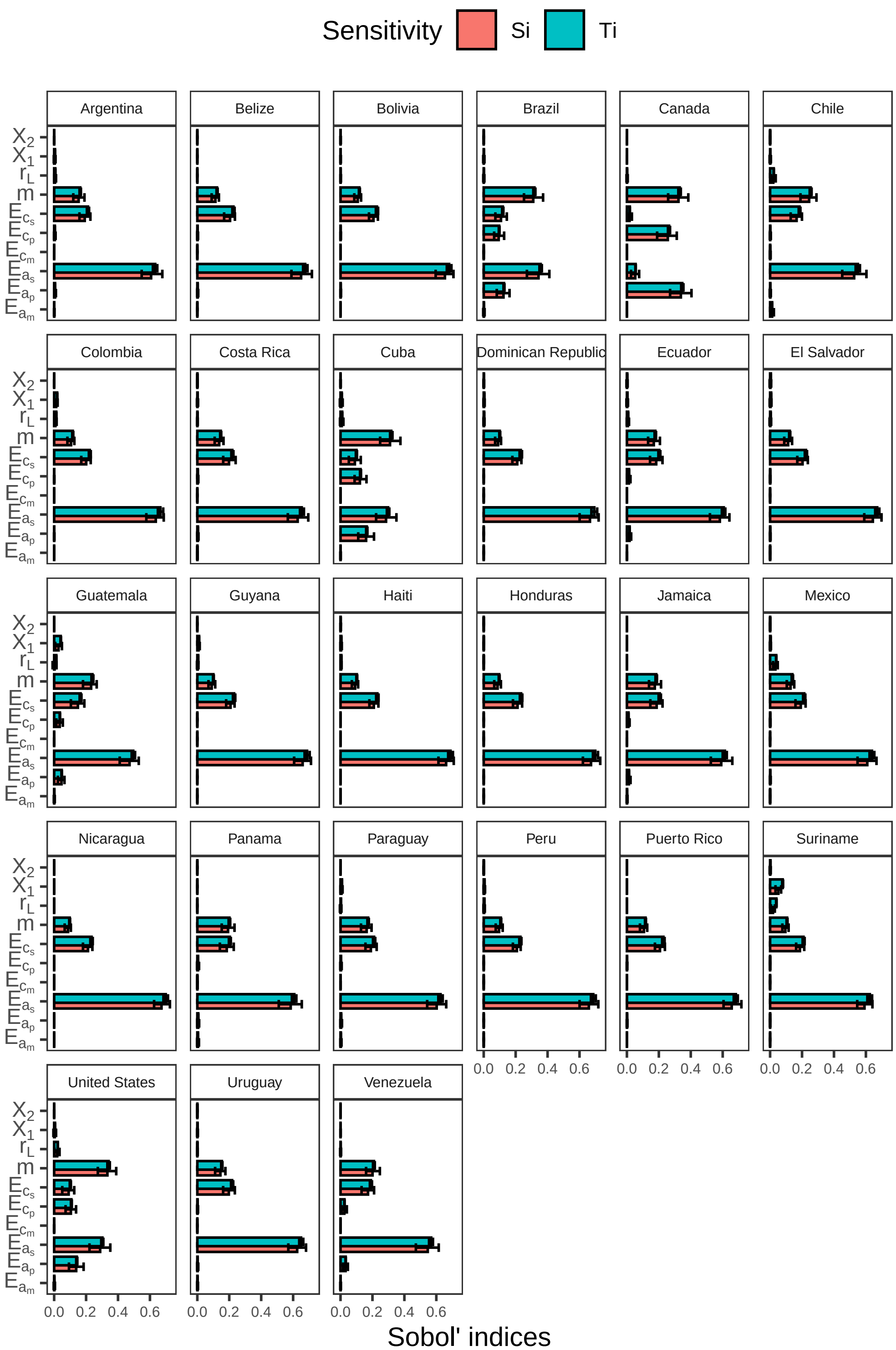
Africa



Sensitivity
Si
Ti
Algeria
Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
Chad
Djibouti
Egypt
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]]
```

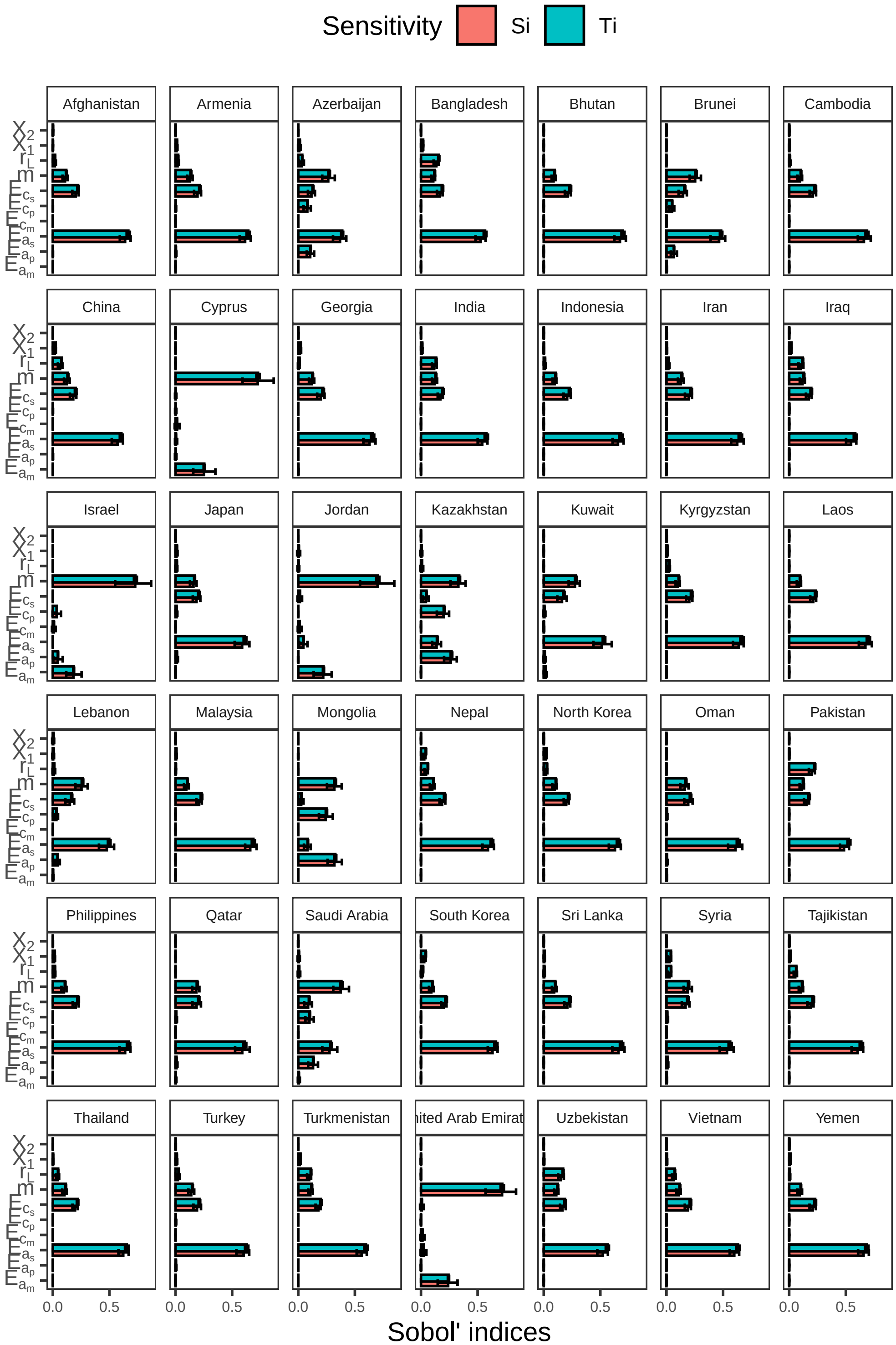
Americas



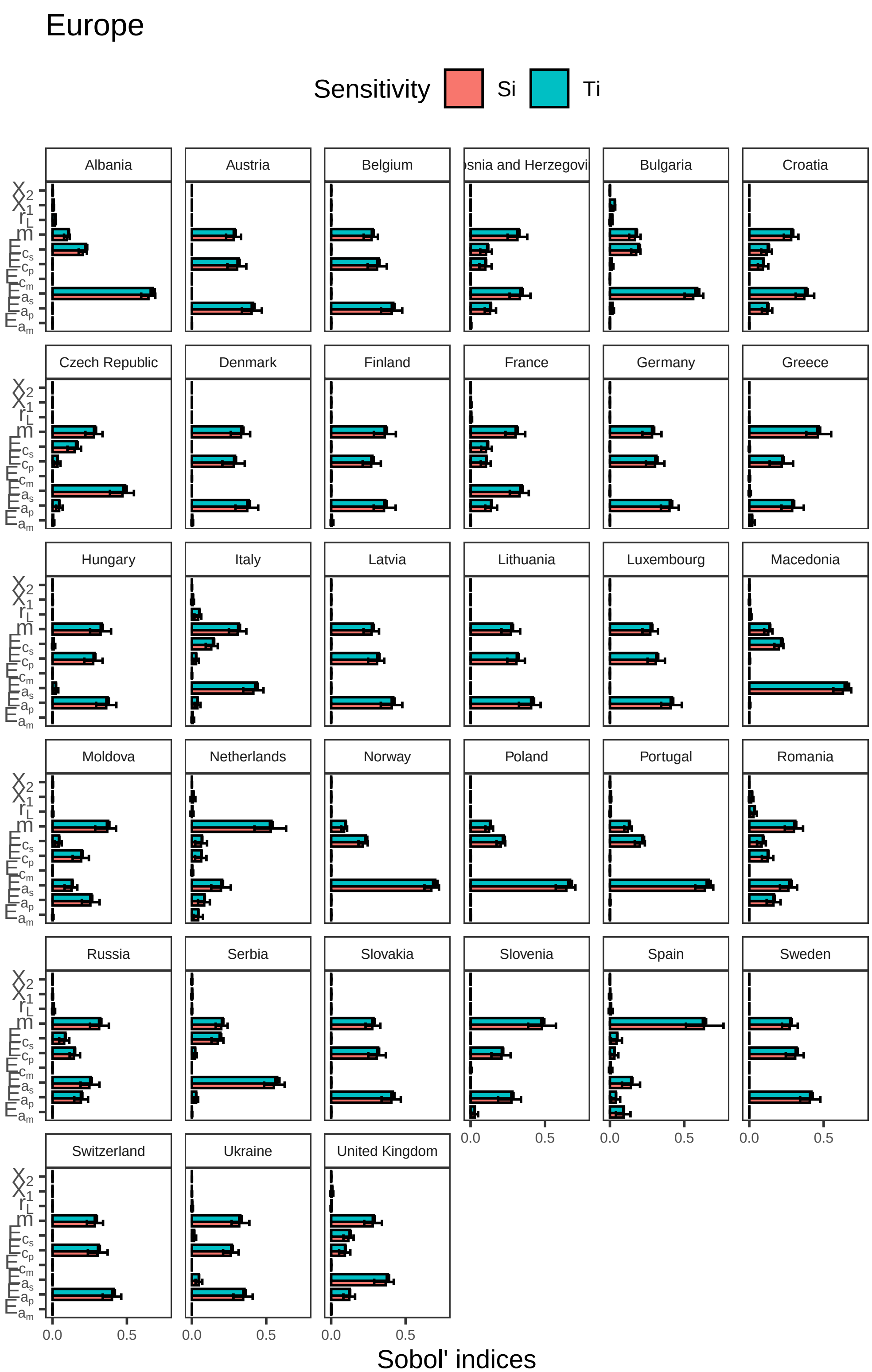
Sensitivity
Si
Ti
Argentina
Belize
Bolivia
Brazil
Canada
Chile
Colombia
Costa Rica
Cuba
Dominican Republic
Ecuador
El Salvador
Guatemala
Guyana
Haiti
Honduras
Jamaica
Mexico
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
Suriname
United States
Uruguay
Venezuela
X_2
X_1
r_L
m
E_{c_s}
E_{c_p}
E_{c_m}
E_{a_s}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


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

Asia

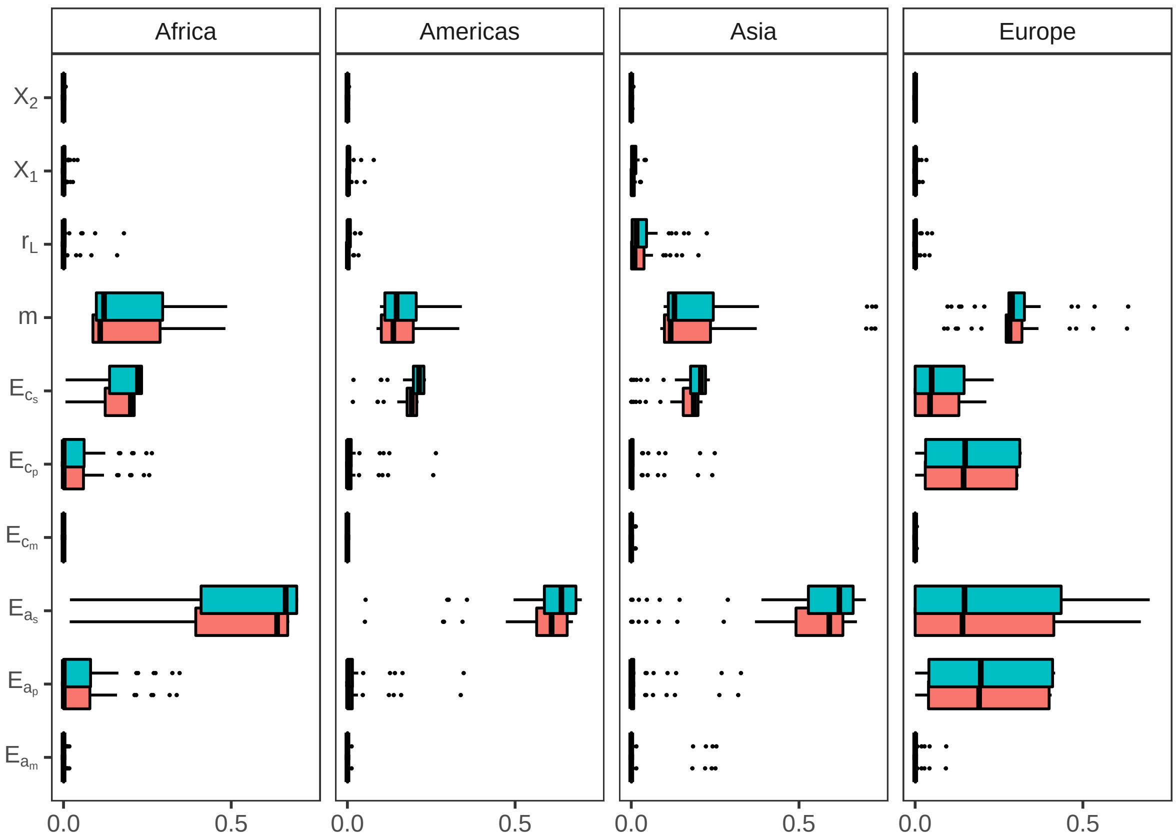

Sensitivity
Si
Ti
Afghanistan
Armenia
Azerbaijan
Bangladesh
Bhutan
Brunei
Cambodia
China
Cyprus
Georgia
India
Indonesia
Iran
Iraq
Israel
Japan
Jordan
Kazakhstan
Kuwait
Kyrgyzstan
Laos
Lebanon
Malaysia
Mongolia
Nepal
North Korea
Oman
Pakistan
Philippines
Qatar
Saudi Arabia
South Korea
Sri Lanka
Syria
Tajikistan
Thailand
Turkey
Turkmenistan
ited Arab Emirat
Uzbekistan
Vietnam
Yemen
0.0
0.5
Sobol' indices

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



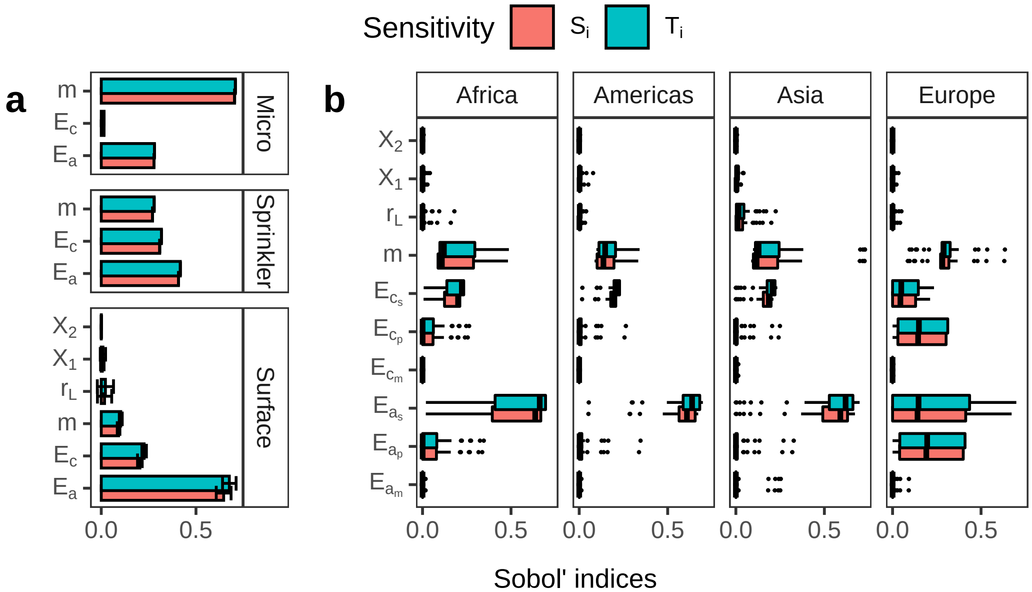

```r
# JAGER INDICES MERGED -----------------------------------------------------------

jager.indices <- jager.ind %>%
  na.omit() %>%
```

```r
  .[!Continent == "Oceania"] %>%
  ggplot(., aes(parameters, original, fill = sensitivity), color = black) +
  geom_boxplot(position = position_dodge(0.6), color = "black",
               outlier.size = 0.1) +
  scale_fill_discrete(name = "Sensitivity", labels = expression(S[i], T[i])) +
  scale_x_discrete(labels = parse_format()) +
  scale_y_continuous(breaks = pretty_breaks(n = 2)) +
  labs(x = "", y = "") +
  facet_grid(~Continent) +
  coord_flip() +
  theme_AP() +
  theme(legend.position = "none")

jager.indices
```




```r
# MERGE INDICES ------------------------------------------------------------------

bottom <- plot_grid(rohwer.indices, jager.indices, ncol = 2,
                    rel_widths = c(0.3, 0.7), labels = "auto")

legend <- get_legend(rohwer.indices + theme(legend.position = "top"))

final <- plot_grid(legend, bottom, ncol = 1, rel_heights = c(0.15, 0.85))
ggdraw(add_sub(final, "Sobol' indices", vpadding = grid::unit(0,"lines"),
```

```
                     y = 6, x = 0.55, vjust = 5.5, size = 10))
```



6 Session information

```
# 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     dbplyr_2.1.1          maps_3.3.0
## [25] rlang_0.4.11          readxl_1.3.1          rstudioapi_0.13
## [28] generics_0.1.0        tikzDevice_0.12.3.1   jsonlite_1.7.2
## [31] magrittr_2.0.1        dotCall64_1.0-1       Matrix_1.3-4
## [34] Rcpp_1.0.7            munsell_0.5.0         fansi_0.5.0
## [37] viridis_0.6.1         lifecycle_1.0.0       stringi_1.7.3
## [40] yaml_2.2.1            plyr_1.8.6            grid_4.0.3
## [43] maptools_1.1-1        crayon_1.4.1          lattice_0.20-44
## [46] haven_2.4.3           hms_1.1.0             knitr_1.33
## [49] pillar_1.6.2          codetools_0.2-18      reprex_2.0.1
## [52] glue_1.4.2            evaluate_0.14         modelr_0.1.8
## [55] vctrs_0.3.8           spam_2.7-0            tzdb_0.1.2
## [58] Rdpack_2.1.2          cellranger_1.1.0      gtable_0.3.0
## [61] assertthat_0.2.1      xfun_0.25             rbibutils_2.2.3
## [64] broom_0.7.9           filehash_2.4-2        viridisLite_0.4.0
## [67] fields_12.5           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
```