Global irrigation water demands biased by unreliable irrigation efficiencies

R code

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1 Preliminary steps

```
# 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())
```

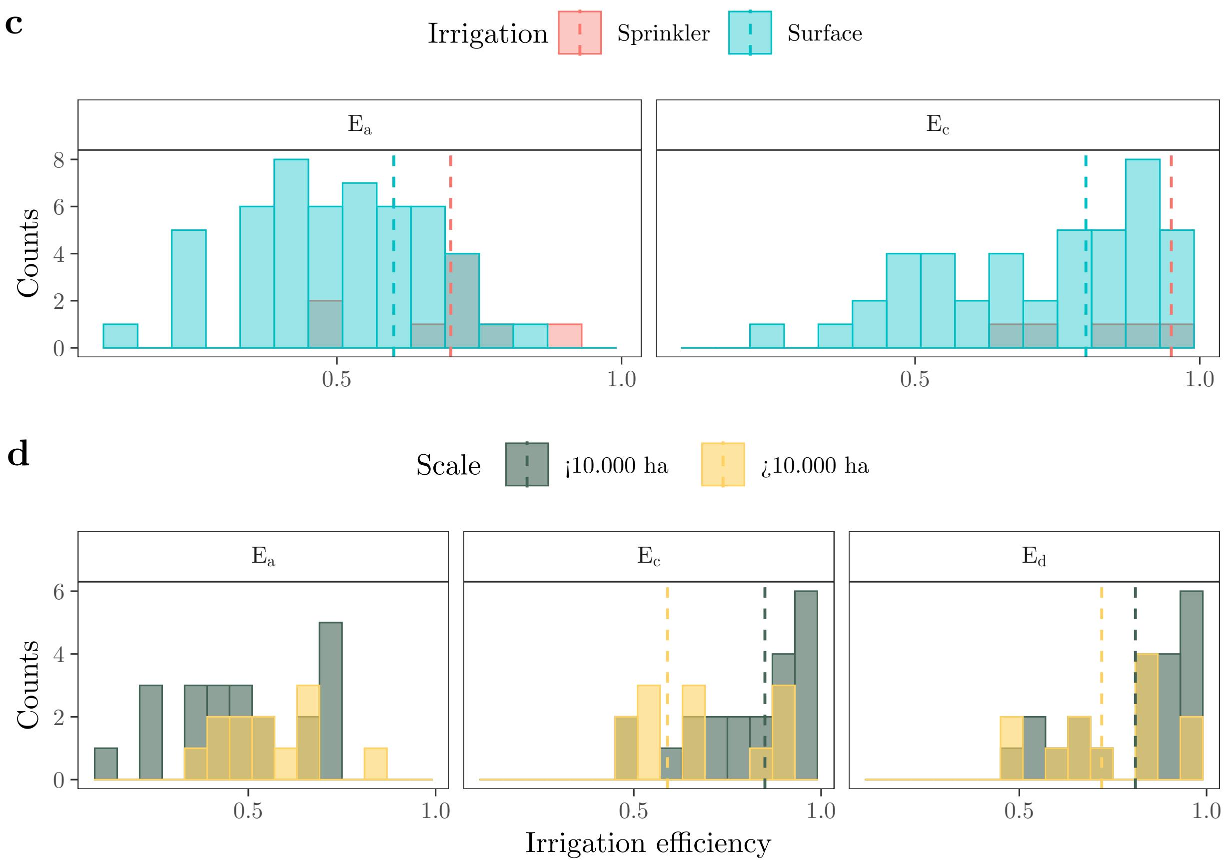
2 Read in data

```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).
```

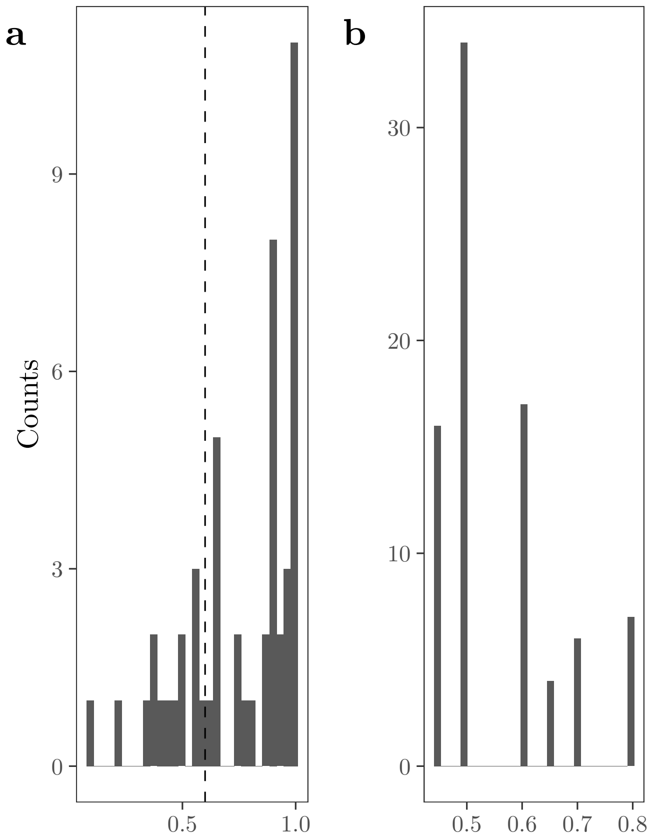
```
bottom
```



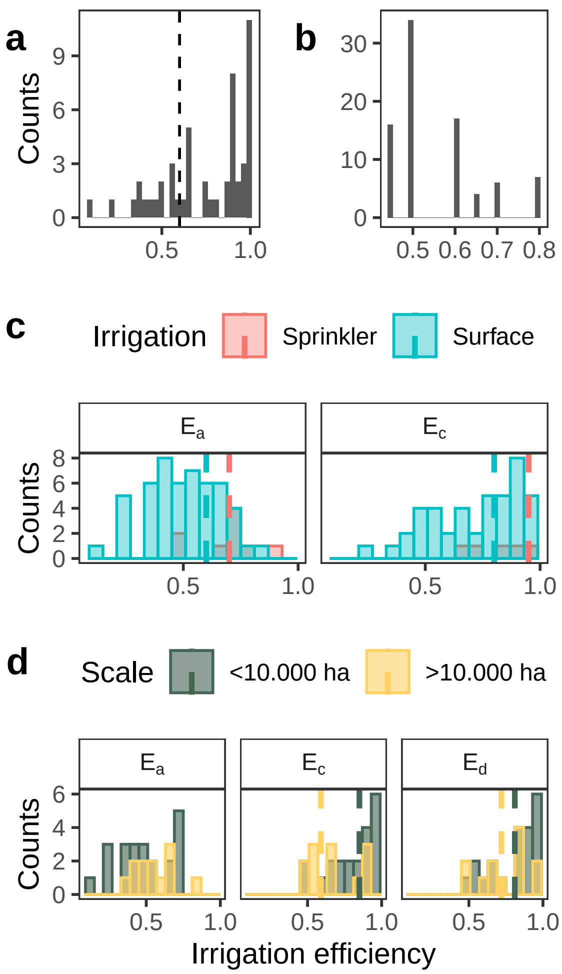

```r
# PLOT USA AND AFRICA ----------------------------------------------------------

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

```r
# 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 * (3 - 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 ----------------

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")) %>%
```

```r
  .[, 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

```r
# 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

```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 ----------------------------------------------------------------------

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") {
```

```r
    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,
```

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

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

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

4 Uncertainty analysis

4.1 Coefficient of variation

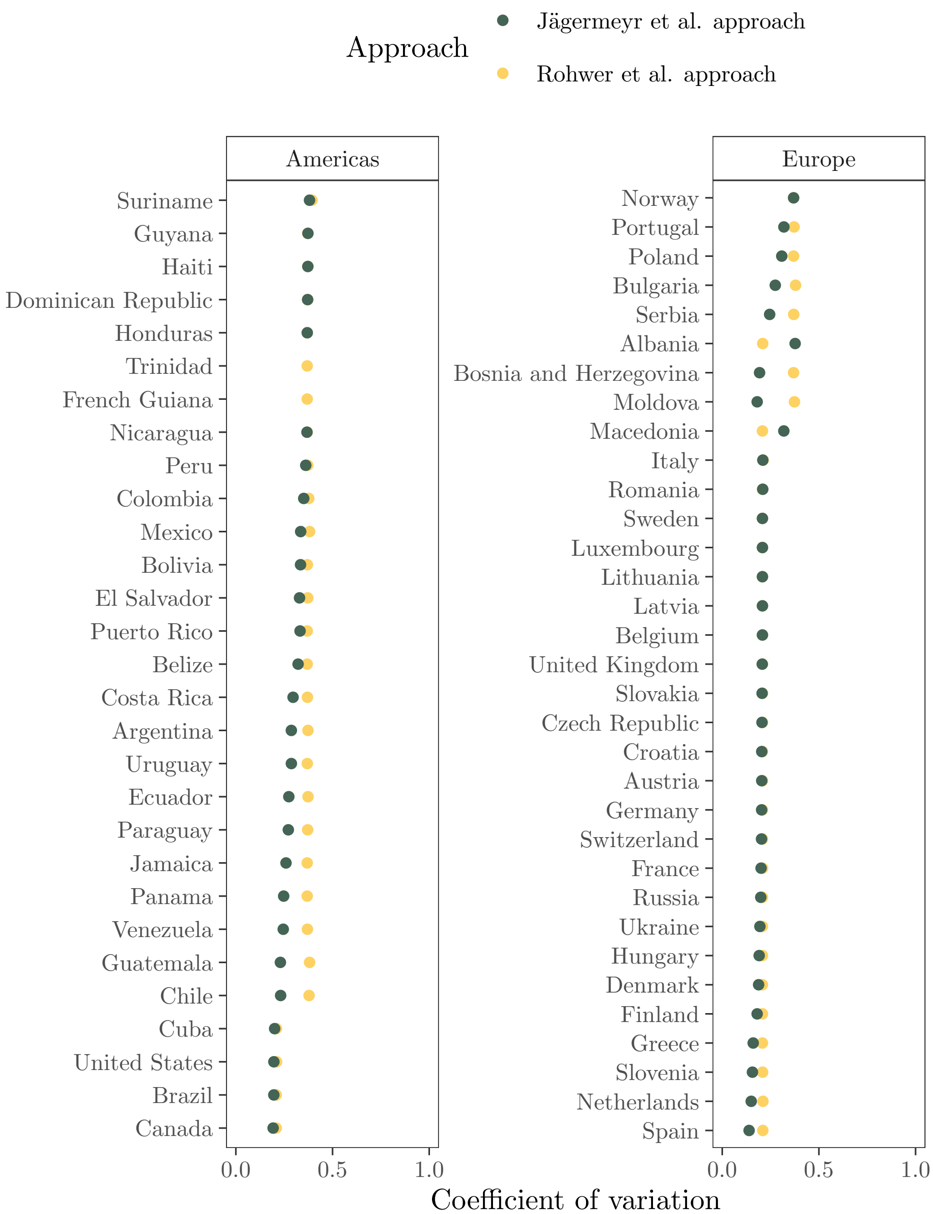
```r
# CALCULATE COEFFICIENT OF VARIATION ---------------------------------------------

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
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
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
```

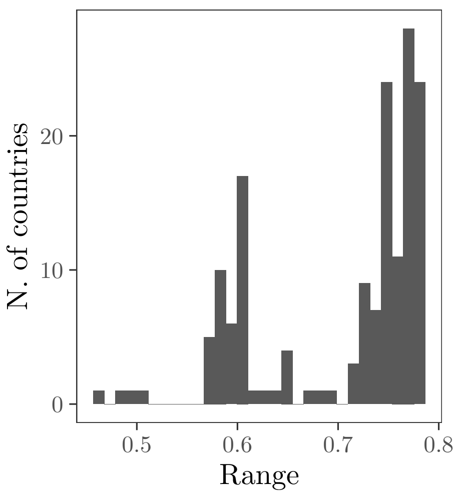
```
## 51:   Africa            Burkina Faso 0.6810580
## 52:   Africa                   Libya 0.6956438
## 53:     Asia              Azerbaijan 0.7146797
## 54:     Asia                   Syria 0.7165713
## 55:   Africa                 Algeria 0.7176049
## 56:     Asia                    Iraq 0.7217608
## 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
```

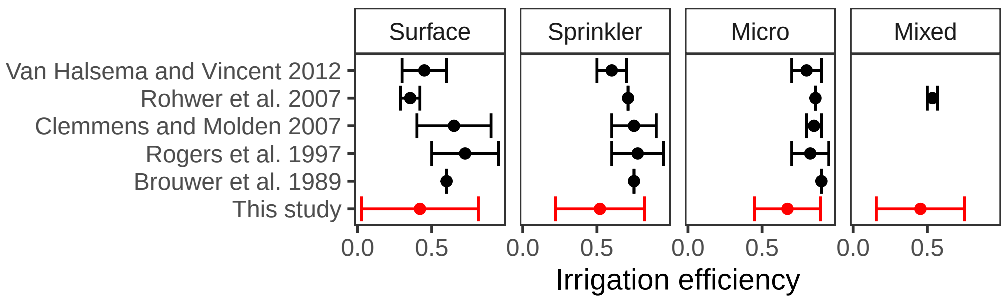
```
ggplot(calc, aes(range)) +
  geom_histogram() +
  labs(x = "Range", y = "N. of countries") +
  theme_AP()
```

```
## `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
```

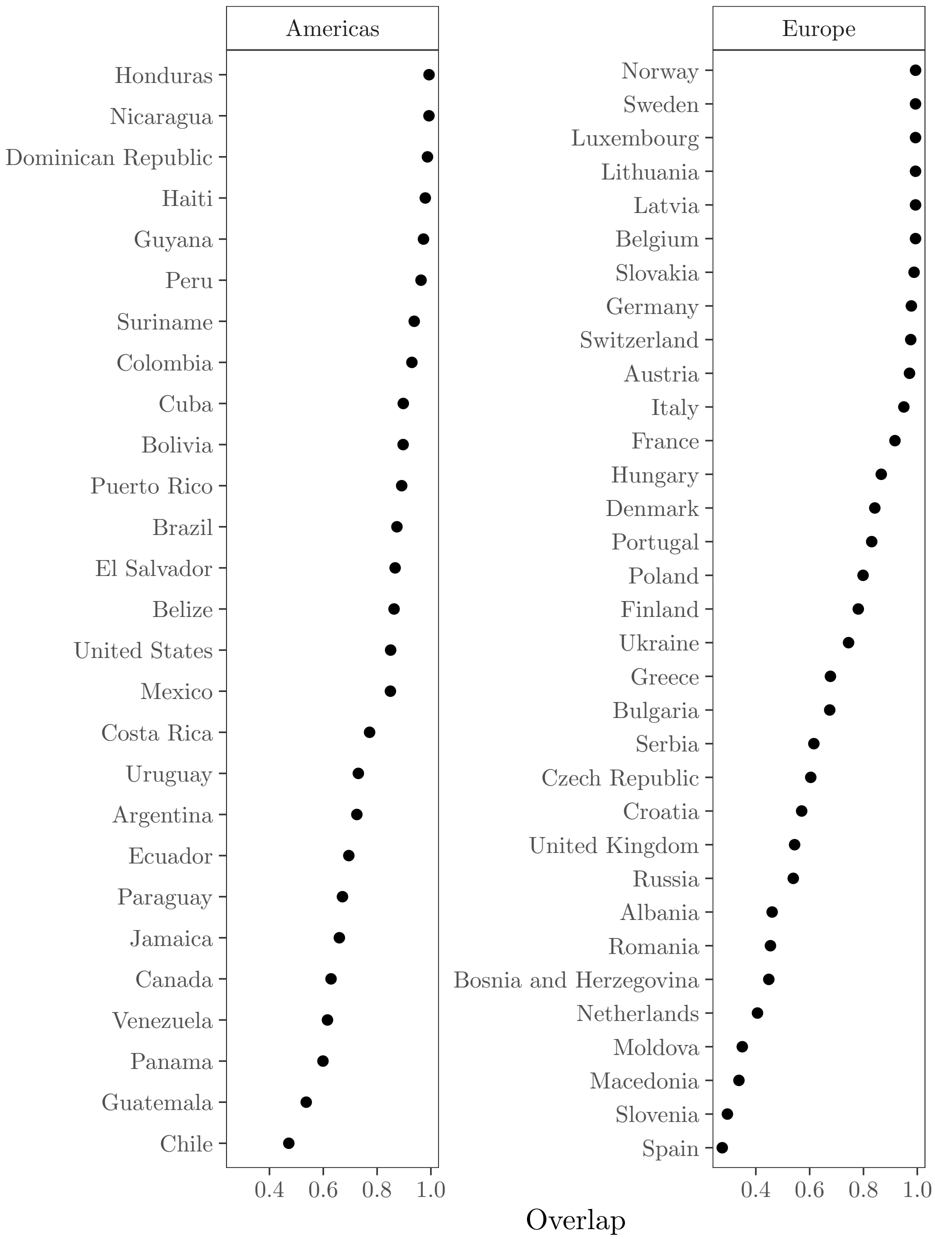
```
## $Africa
## Surface-Sprinkler     Surface-Mixed   Sprinkler-Mixed
##         0.3329115         0.5084454         0.5255184
##
## $Americas
## Surface-Mixed
##     0.5084078
##
## $Asia
## Surface-Micro Surface-Mixed   Micro-Mixed
##    0.05314604    0.42996793    0.07870342
##
## $Europe
## Surface-Sprinkler     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")]

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
```

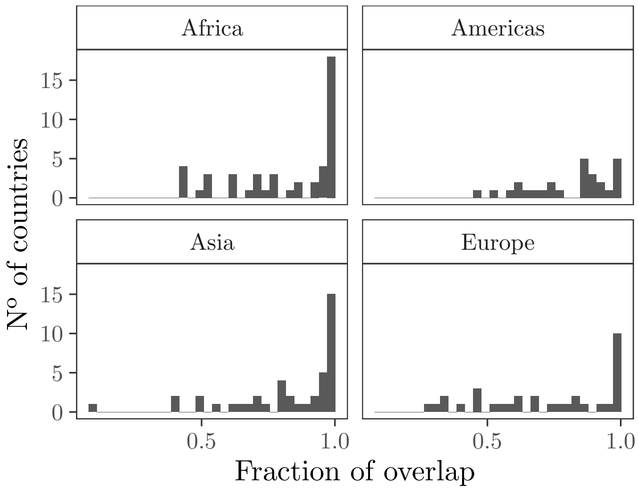
```
## [[1]]
```


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

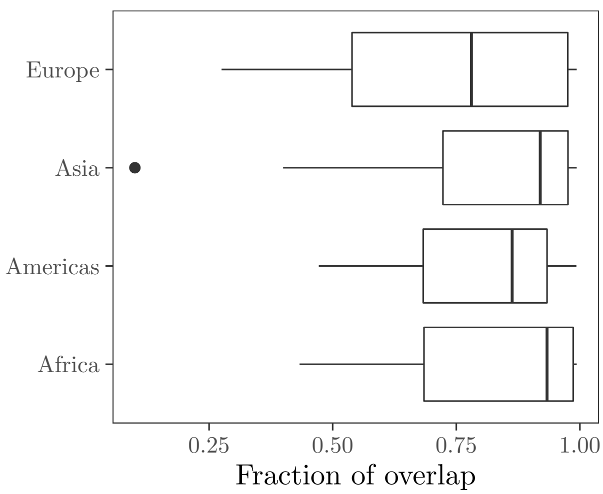
```
##
## [[2]]
```




```
# 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")
```




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




```r
# 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)]
```

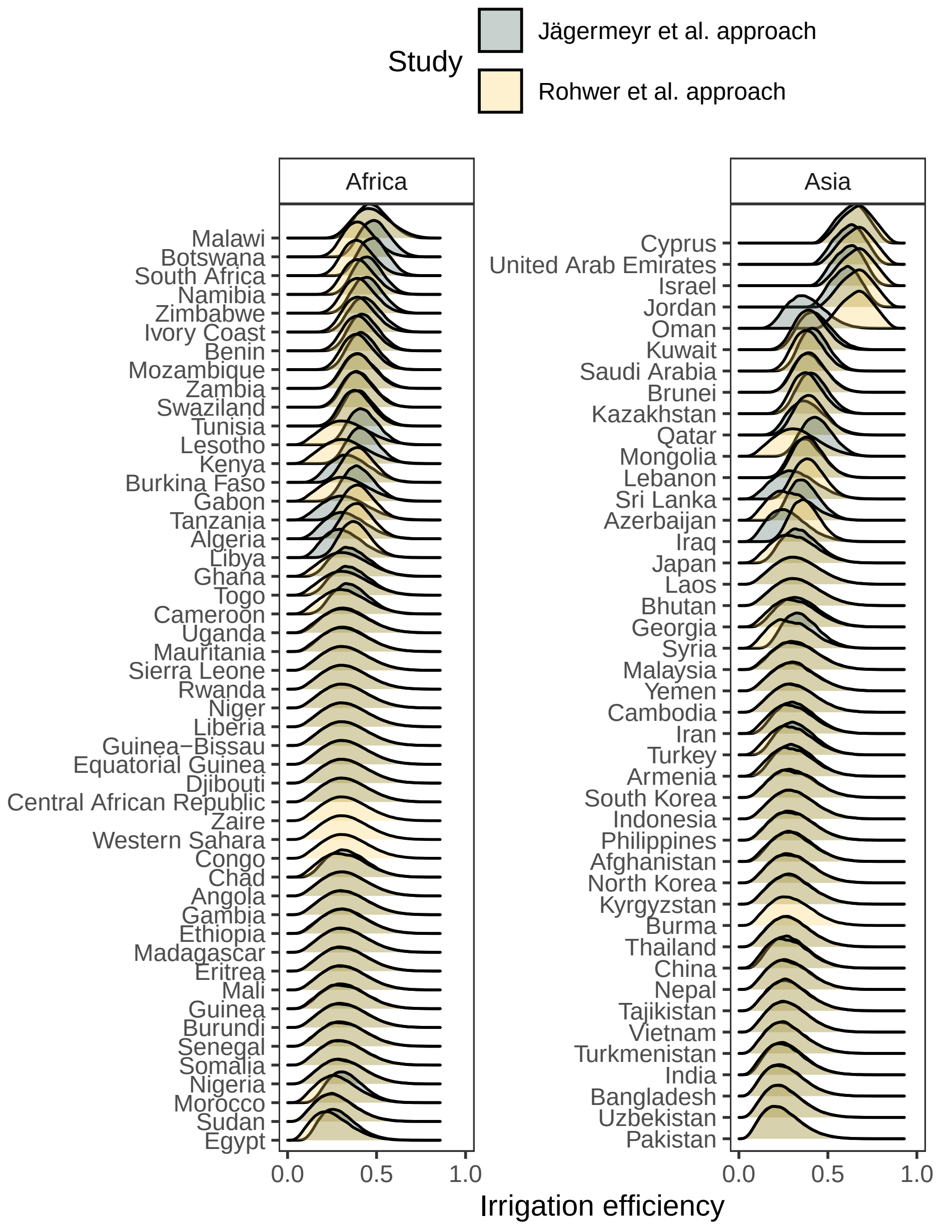
```
##     Country Surface_fraction Sprinkler_fraction Drip_fraction   IFT
## 1:     Oman            0.793              0.113         0.094 Micro
## 2: Slovenia            0.000              0.693         0.307 Mixed
## 3:    Spain            0.297              0.226         0.478 Mixed
```

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

gg <- list()
```

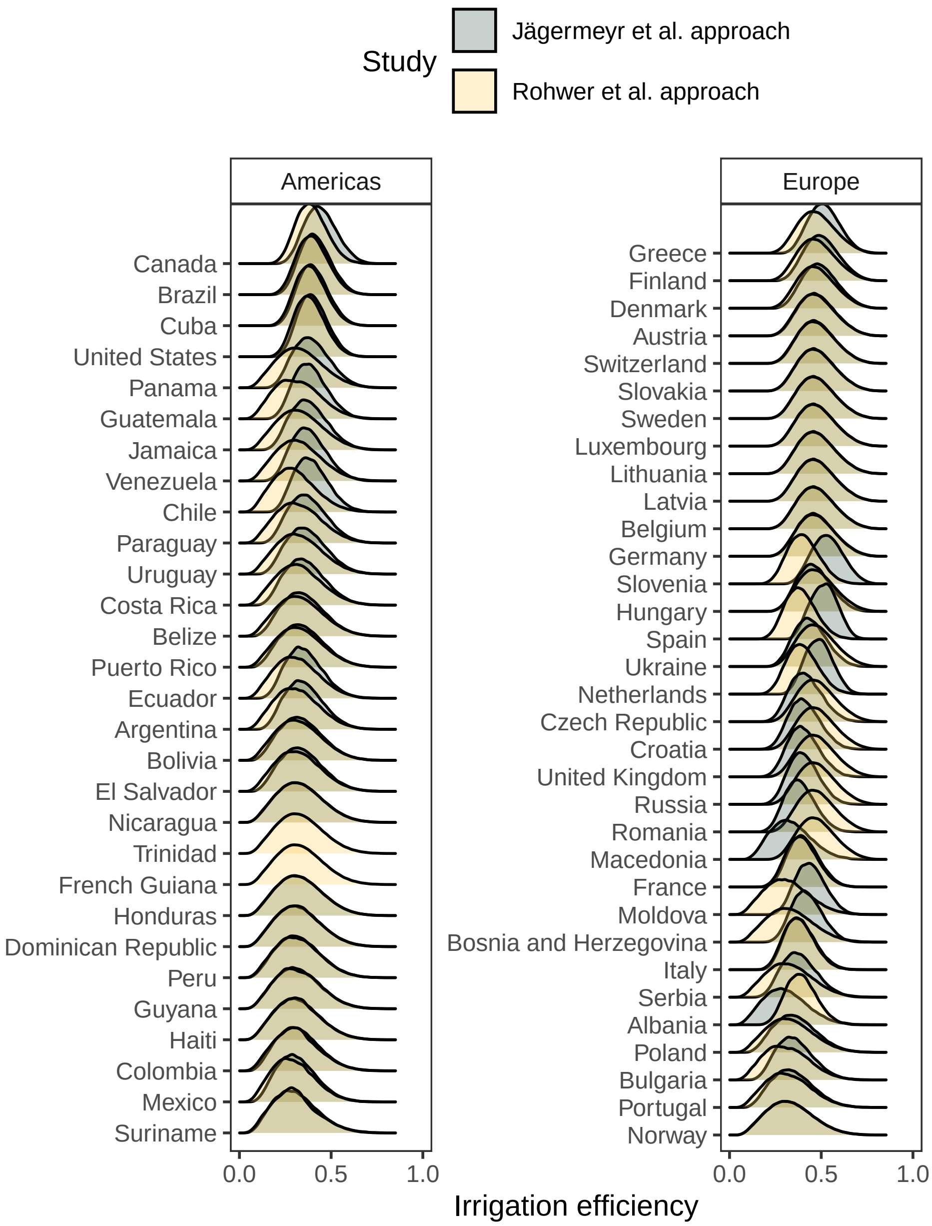
```r
for (i in 1:length(list_continents)) {
  gg[[i]] <- ggplot(uncertainty.dt[Continent %in% list_continents[[i]]],
                    aes(x = V1, y = fct_reorder(Country, V1), fill = Study)) +
    geom_density_ridges(scale = 2, alpha = 0.3) +
    labs(x = "Irrigation efficiency", y = "") +
    facet_wrap(~Continent, 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
```



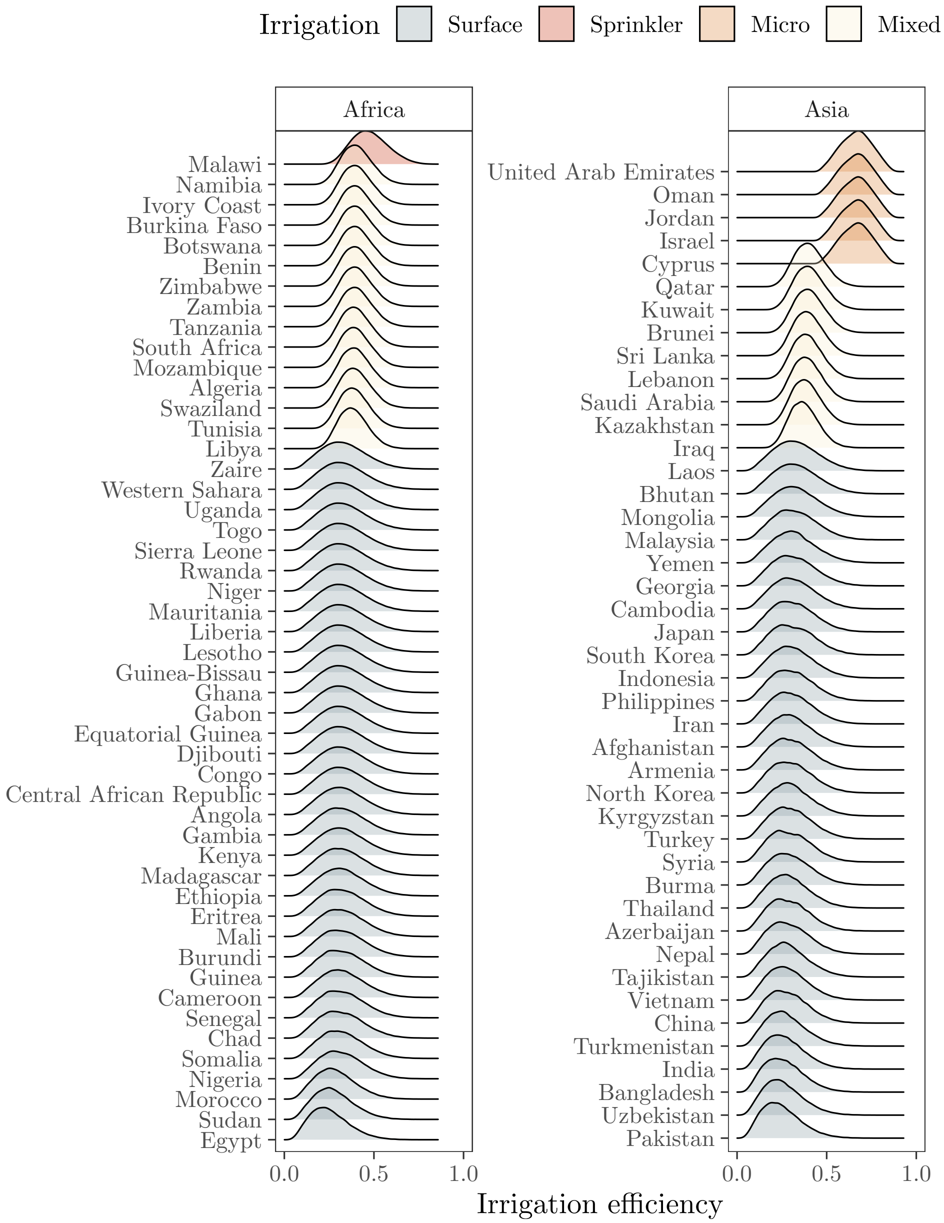

```
# PLOT UNCERTAINTY IN EACH IRRIGATION TECHNOLOGY ---------------------------------

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() +
```

```
    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
```

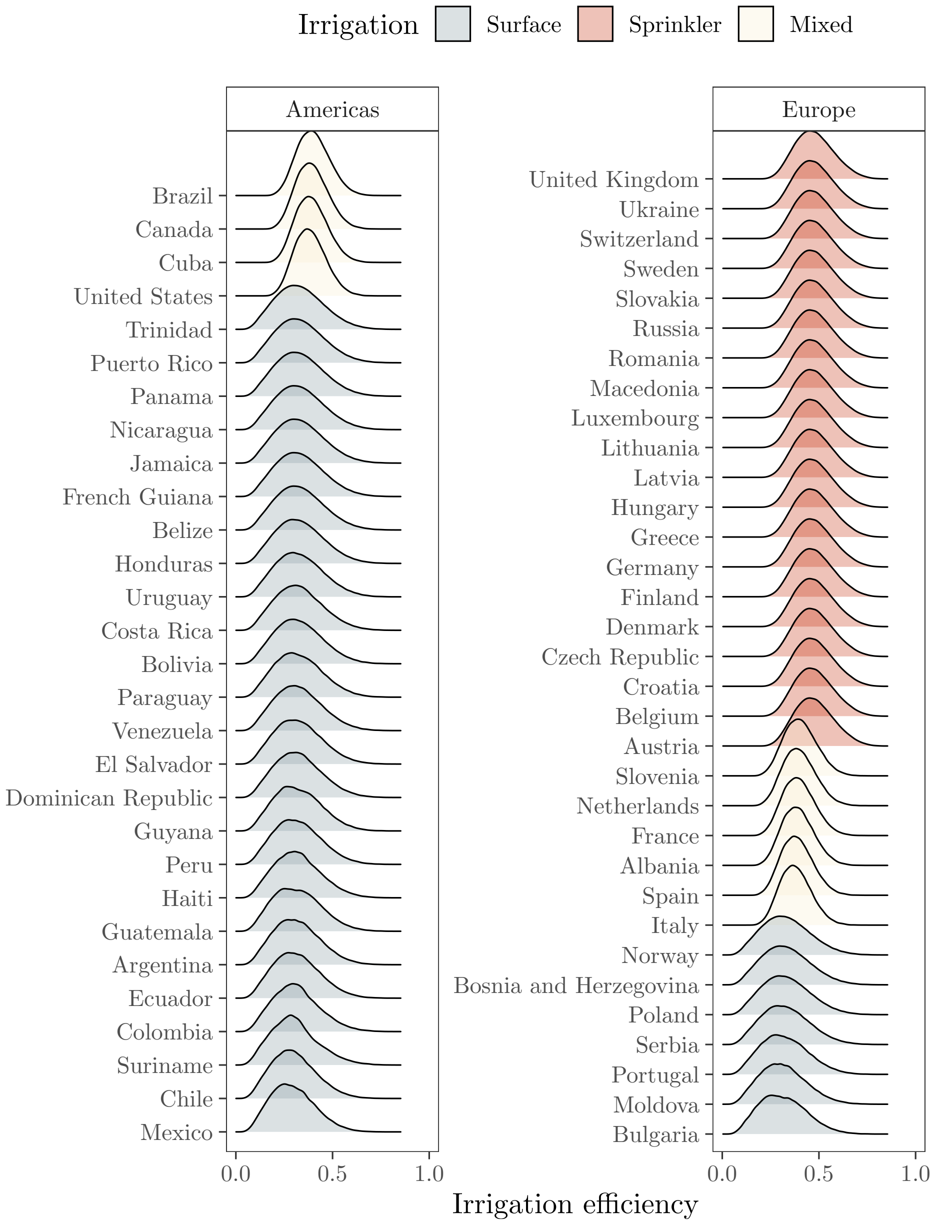
```
## [[1]]
```

```
## 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")]
```

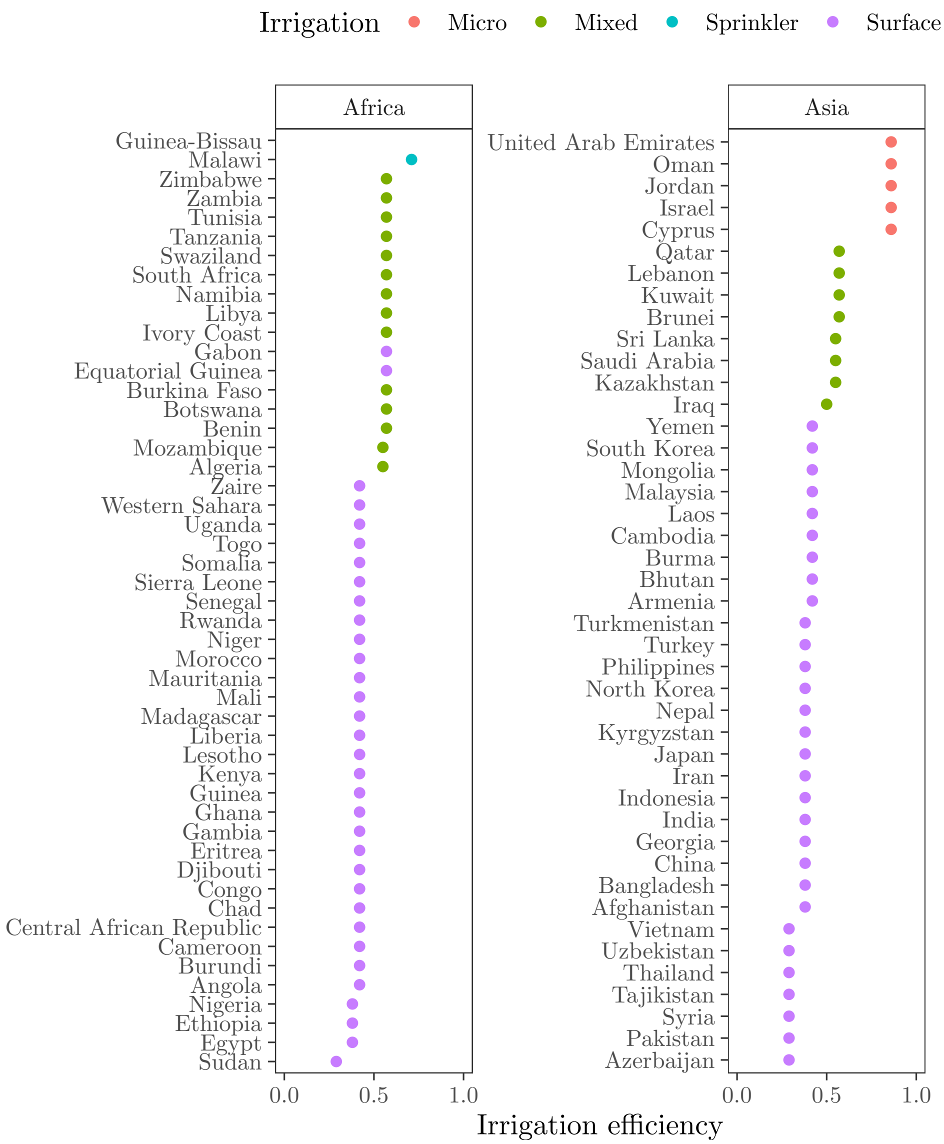
```
## Warning in countrycode_convert(sourcevar = sourcevar, origin = origin, destination = dest,
```

```
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),
```

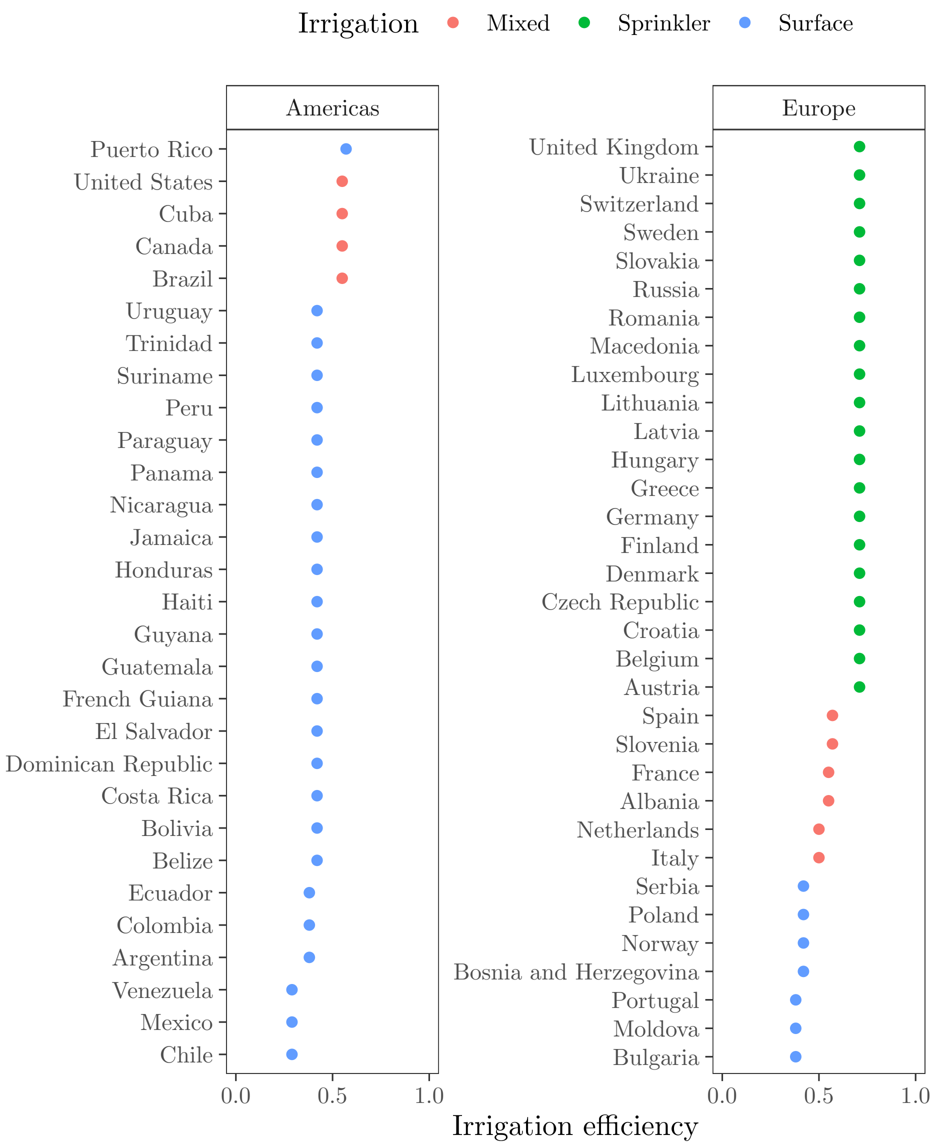
```
                        limits = c(0, 1)) +
    facet_wrap(~Continent, scales = "free") +
    scale_color_discrete(name = "Irrigation") +
    theme_AP()
}

dd
```

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

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

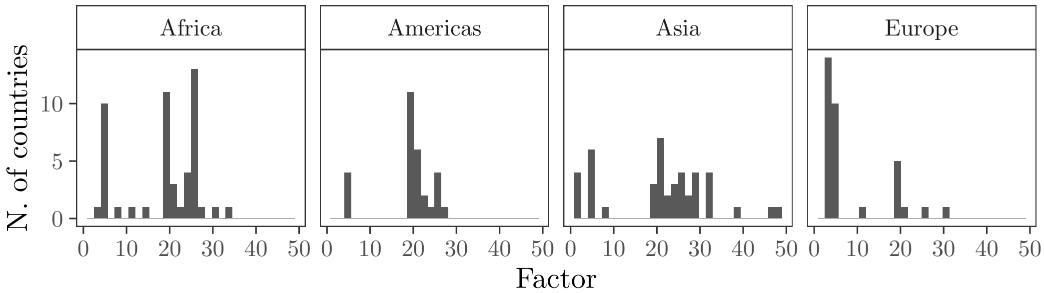



```
##
## [[2]]
```




```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               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

```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],
                             origin = "country.name",
                             destination = "un")] %>%
      .[, Country:= countrycode(out[, Code],
                                origin = "un",
```

```r
                                  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")
```

```
# 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)

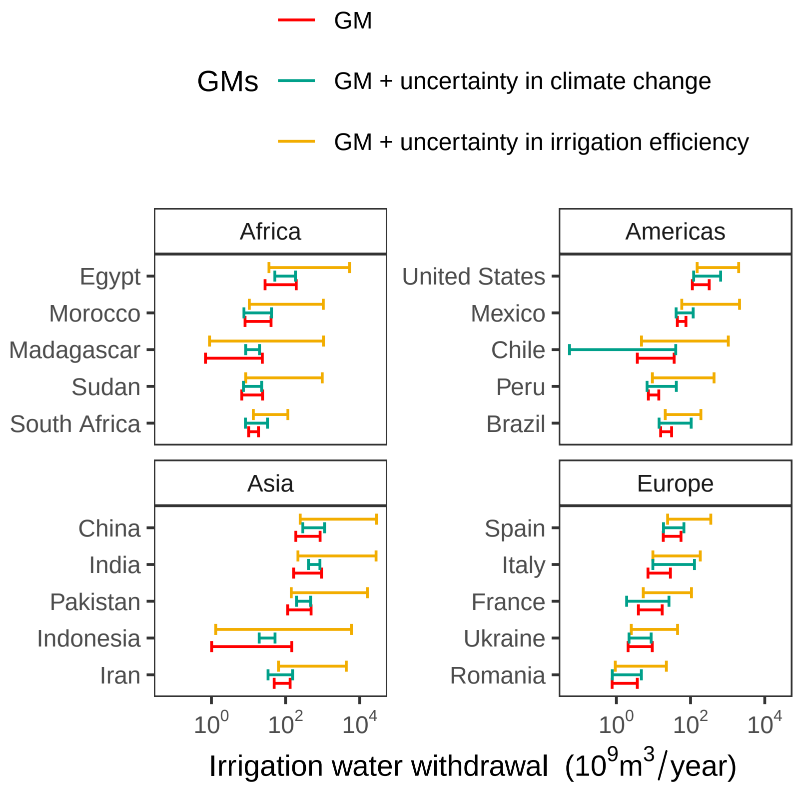
```
# READ IN FILES ON CLIMATE CHANGE UNCERTAINTY (2050) -----------------------------

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"
)
```

```r
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",
```

```r
                    "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))
```

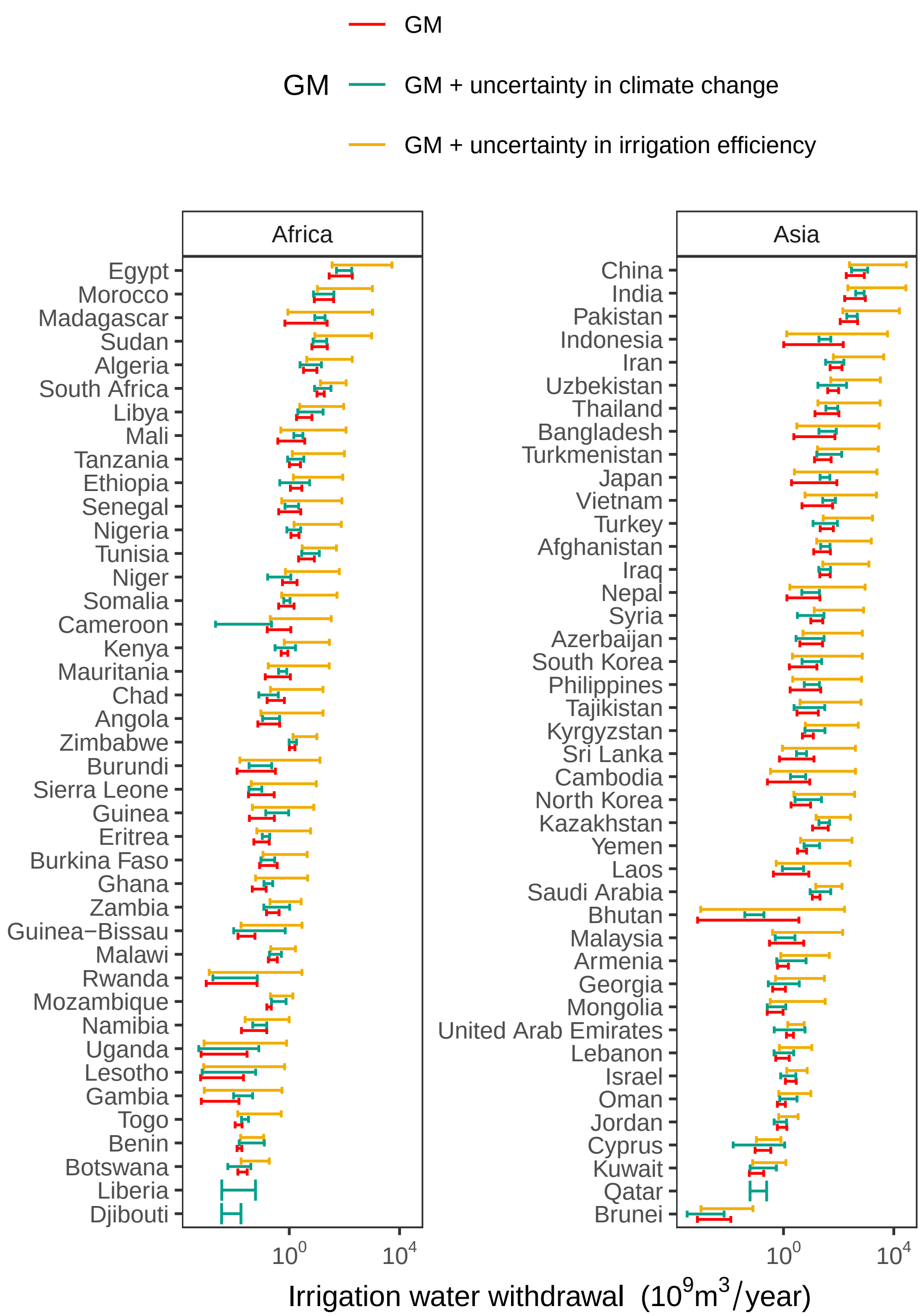



```
# EXPORT -----------
fwrite(all.uncertainties, "all.uncertainties.csv")
```

```
# 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 = "") +
```

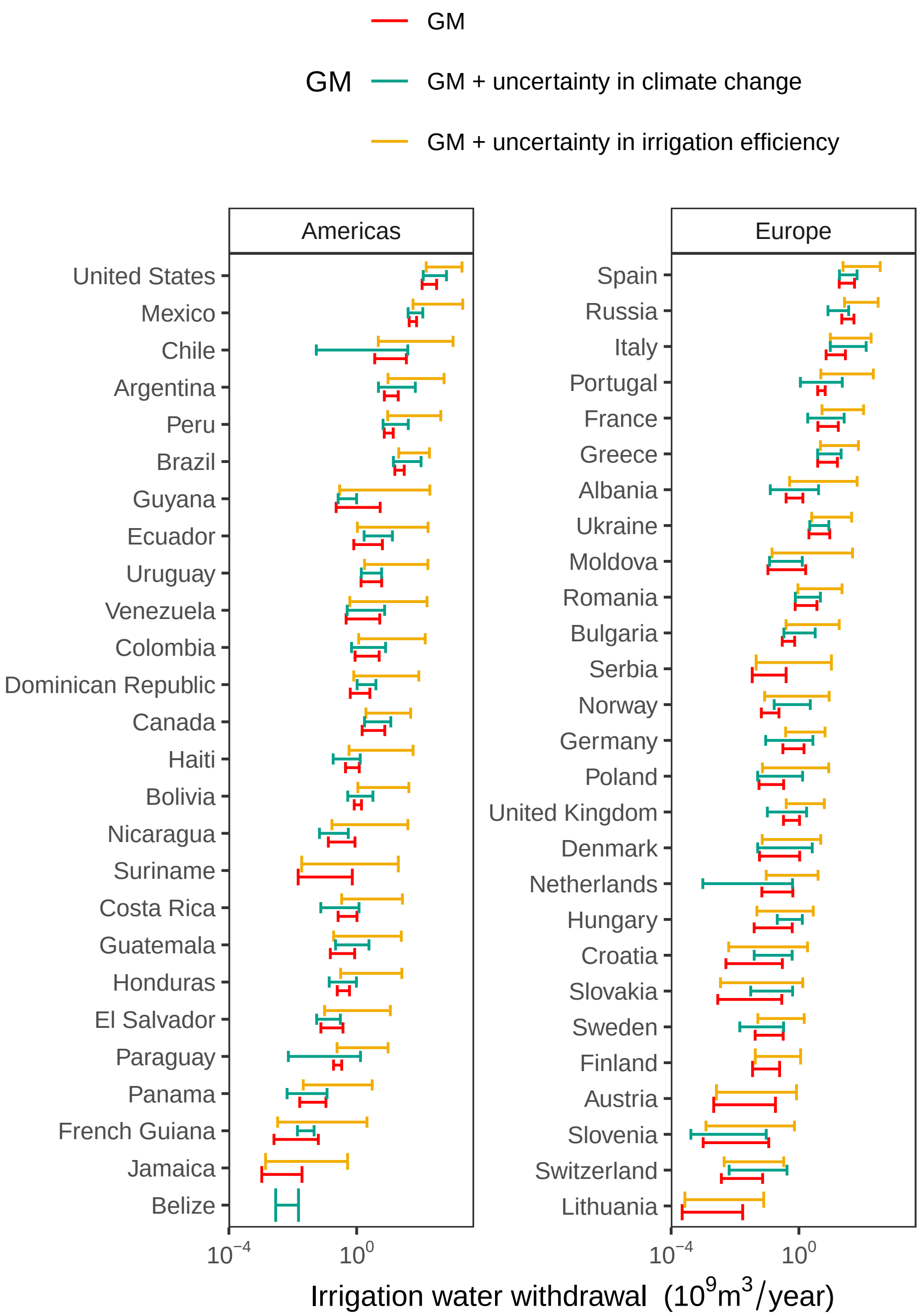
```
    facet_wrap(~Continent, scales = "free_y") +
    coord_flip() +
    theme_AP() +
    guides(color = guide_legend(nrow = 3, byrow = TRUE))
}

dd
```

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




```
##
```

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




```r
# 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

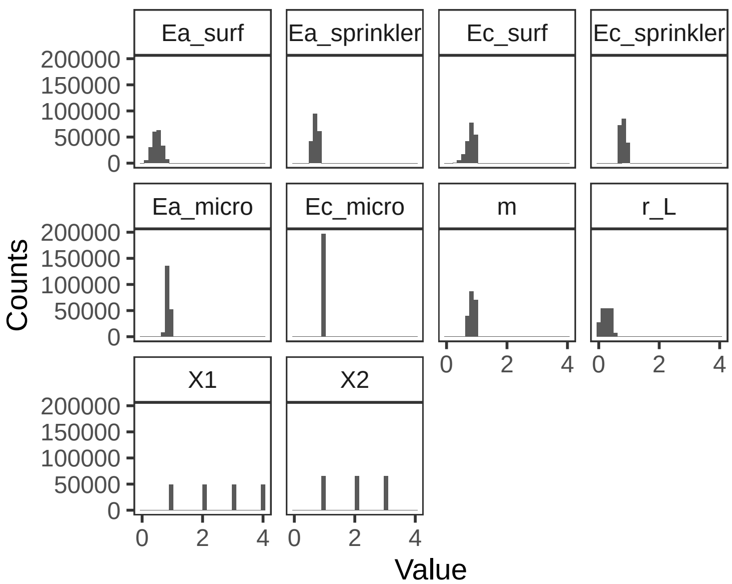
```
# SAMPLE MATRIX DISTRIBUTIONS -----------------------------------------------

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

```
                  "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
```

```
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`.
```



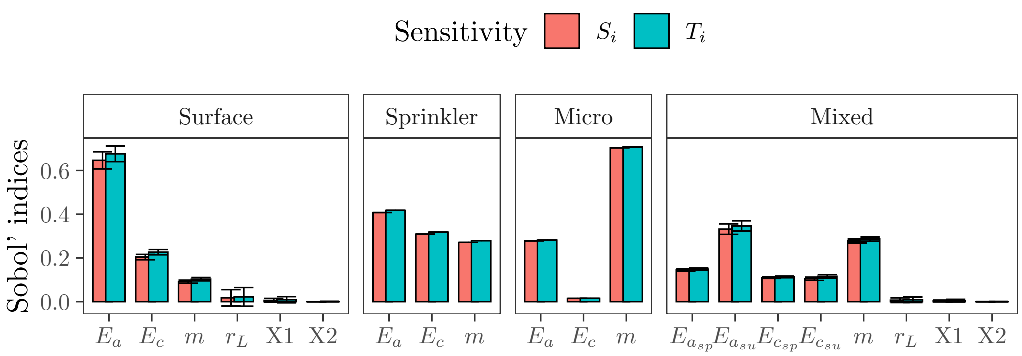

```
# EXTRACT SOBOL' INDICES ----------------------------------------------------

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 ==
```

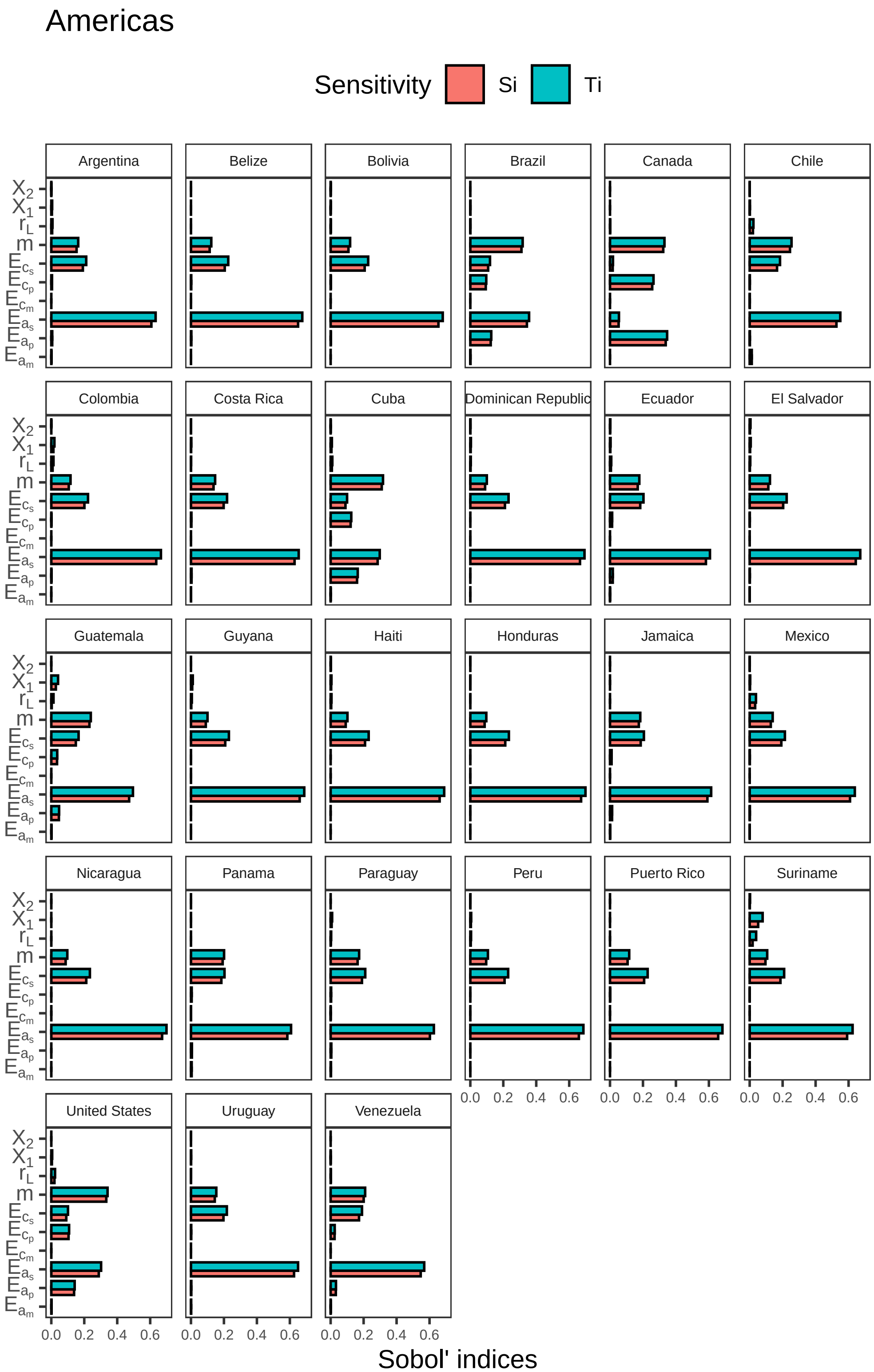
```
## Warning in countrycode_convert(sourcevar = sourcevar, origin = origin, destination = dest,
```

```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)
)
```

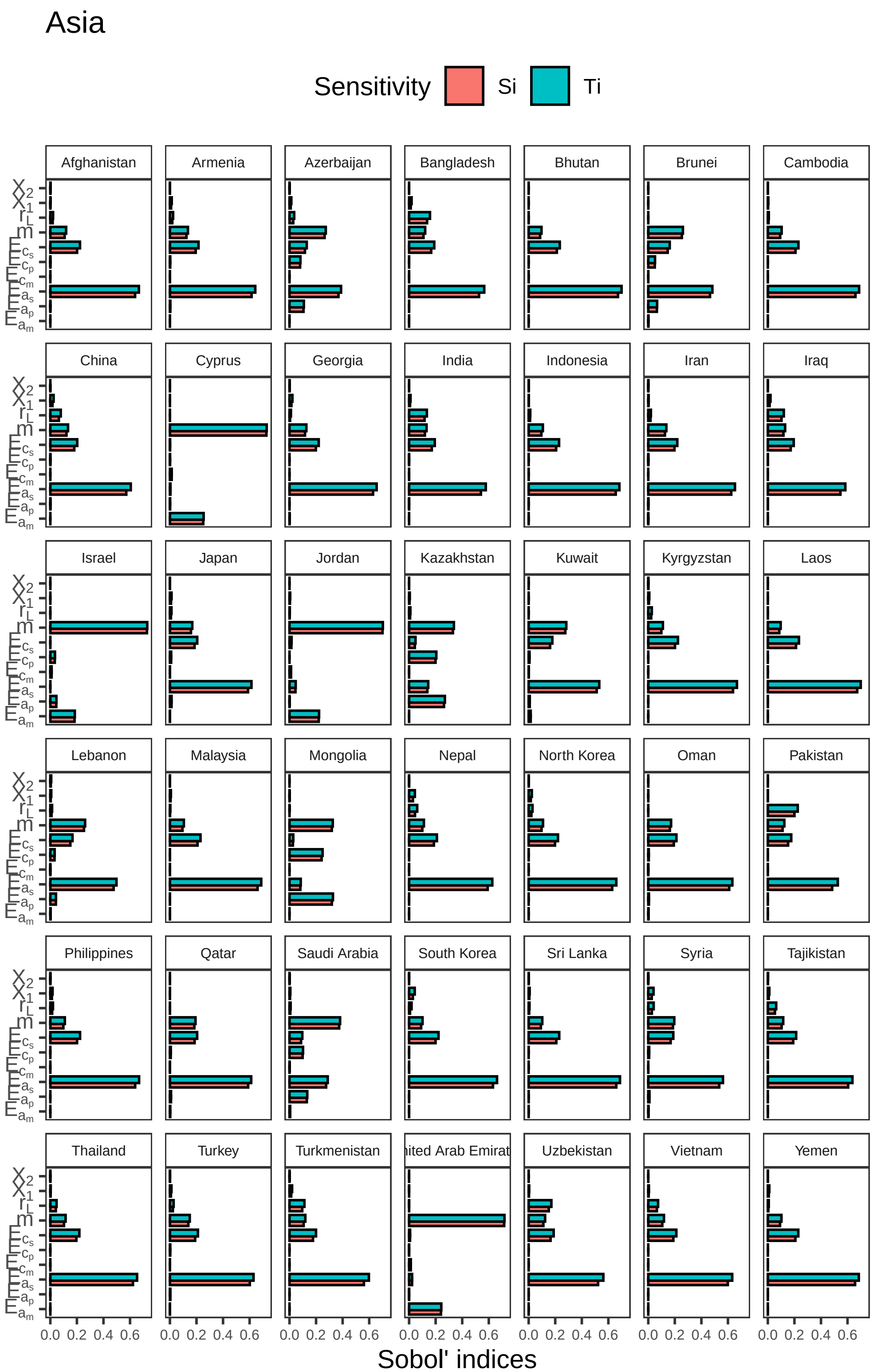
```
## [[1]]
```

Africa
Sensitivity
Si
Ti
Algeria
Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
Central African Republic
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

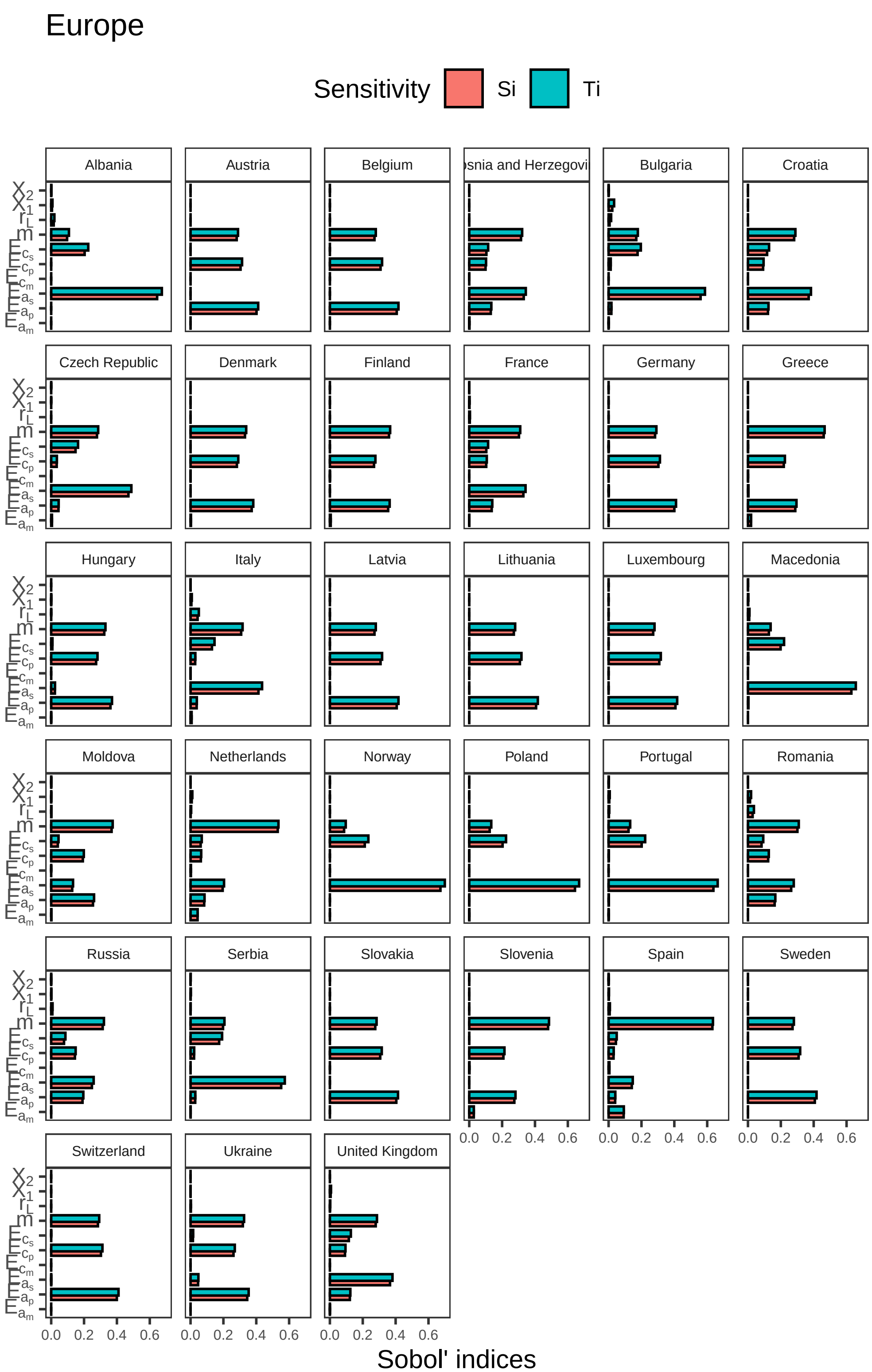

```
##
## [[2]]
```


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]]
```




```r
# 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
```