Global irrigation water demands biased by unreliable irrigation efficiencies

R code

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Contents

```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"))

# 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())
```

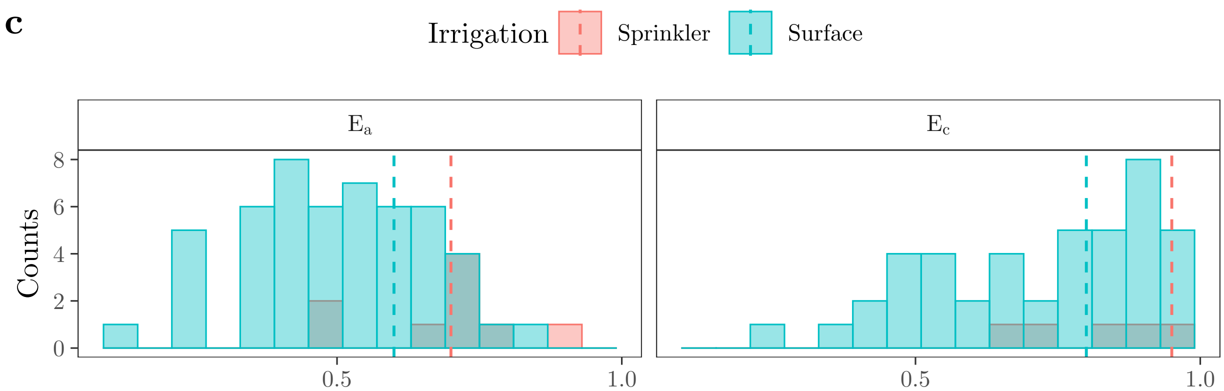
1 Read in data

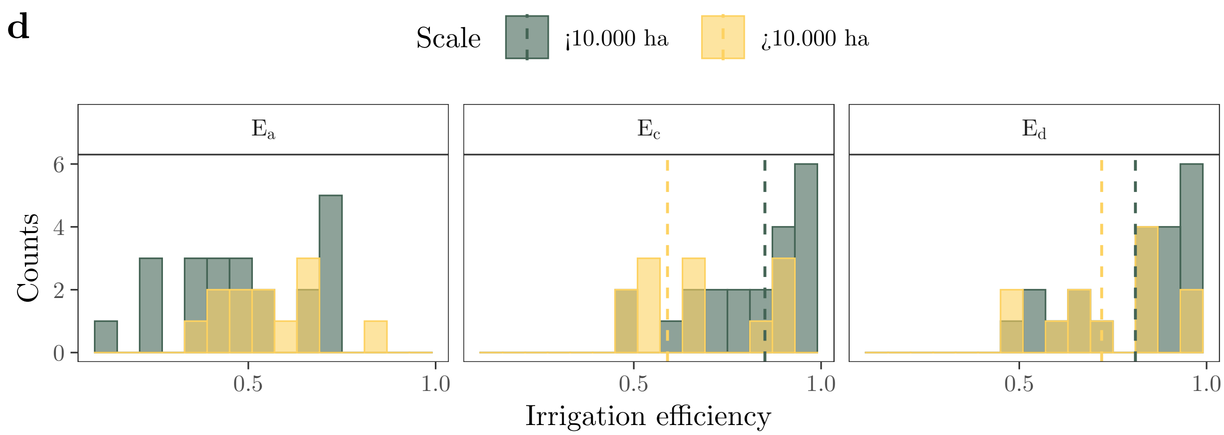
```r
# READ IN DATA ---------------------------------------------------------------------

# 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
```

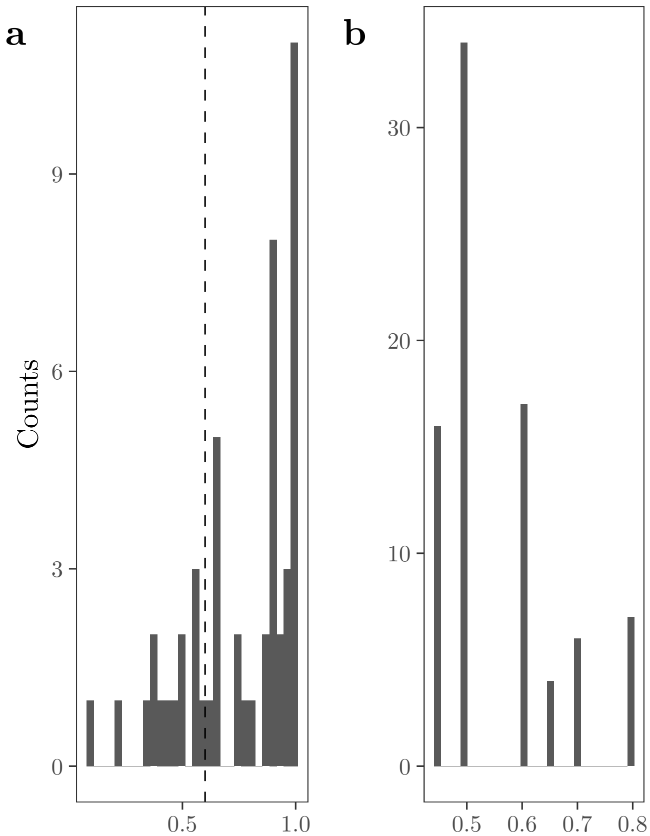




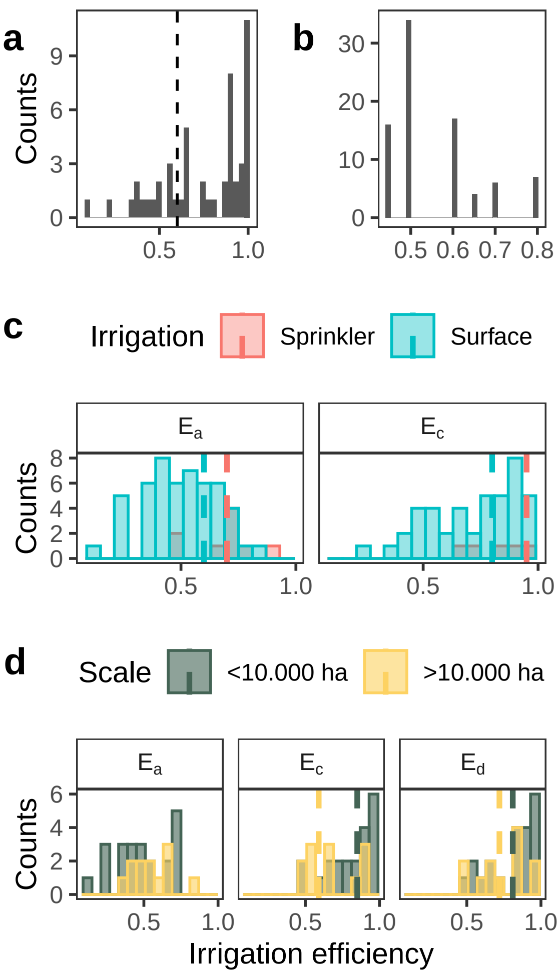

```r
# PLOT USA AND AFRICA -------------------------------------------------------------

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))
```



2 The model

2.1 Function to create sample matrix

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

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

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

```
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)
}
```

2.2 Define distributions

```
# 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)
)
```

2.3 Uncertainty in the proportion of large-scale irrigated areas

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

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

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

2.4 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
  countries.frac <- countries.list[[Country]]

  if(IFT == "Surface" | IFT == "Mixed") {

  mat[, "Proportion_large"] <- qunif(mat[, "Proportion_large"],
                                      countries.frac$min, countries.frac$max)
  }
  out <- list(tmp$parameters, mat)
  names(out) <- c("parameters", "matrix")
  return(out)
}
```

2.5 Run 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") {

    Mf <- mat[, "m"] - 0.5 * mat[, "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"] - 0.5 * mat[, "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"] - 0.5 * mat[, "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

  }

  if(IFT == "Jager") {
    boot <- FALSE
    R <- NULL
  } else {
    boot <- TRUE
    R <- R
  }

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

2.6 Define settings

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

N <- 2^13
R <- 10^2
```

2.7 Run model

```
# 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)
}
```

2.8 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",
                                                  "The proportion of IFTs is known",
                                                  "The proportion of IFTs is not known")]
```

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

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

```r
# 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 0.4650154
##   2:      Asia   United Arab Emirates 0.4889552
##   3:      Asia                 Israel 0.4901008
##   4:      Asia                 Jordan 0.5107562
##   5:    Africa                  Benin 0.5460129
##   6:      Asia                 Kuwait 0.5519086
##   7:    Africa                Tunisia 0.5546542
##   8:    Africa             Mozambique 0.5549232
##   9:      Asia           Saudi Arabia 0.5556065
##  10:    Africa                Namibia 0.5567580
##  11:    Europe                  Italy 0.5576075
##  12:  Americas          United States 0.5586242
##  13:  Americas                 Brazil 0.5586775
##  14:      Asia             Kazakhstan 0.5595325
##  15:    Africa            Ivory Coast 0.5607401
##  16:    Africa               Zimbabwe 0.5626920
##  17:  Americas                   Cuba 0.5643215
##  18:    Europe                 France 0.5645315
##  19:    Africa              Swaziland 0.5681810
##  20:    Africa                 Zambia 0.5700714
##  21:  Americas                 Canada 0.5722302
##  22:    Africa           South Africa 0.5749587
##  23:    Africa               Botswana 0.5802624
##  24:      Asia                 Brunei 0.5816775
##  25:    Europe                  Spain 0.5824526
##  26:      Asia                Lebanon 0.5850318
##  27:    Europe                 Greece 0.5923817
##  28:    Africa                 Malawi 0.5923817
##  29:    Europe                Austria 0.5941574
##  30:    Europe            Netherlands 0.5954245
##  31:    Europe            Switzerland 0.5960538
##  32:    Europe                Denmark 0.5963984
##  33:    Europe               Slovakia 0.5977046
##  34:    Europe                Finland 0.5987308
##  35:    Europe                Germany 0.5987520
##  36:    Europe                Belgium 0.6002391
##  37:      <NA>               Byelarus 0.6002391
```

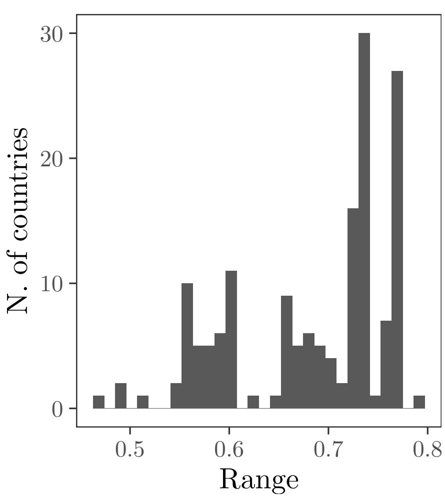
```
## 38:    Europe                   Latvia 0.6002391
## 39:    Europe                Lithuania 0.6002391
## 40:    Europe               Luxembourg 0.6002391
## 41:    Europe                   Sweden 0.6002391
## 42:    Europe                  Hungary 0.6051666
## 43:      Asia                    Qatar 0.6074024
## 44:    Europe                  Ukraine 0.6224391
## 45:    Europe                 Slovenia 0.6463006
## 46:    Europe                   Russia 0.6523247
## 47:    Europe           Czech Republic 0.6526027
## 48:    Europe                 Bulgaria 0.6560802
## 49:  Americas                  Ecuador 0.6560802
## 50:      Asia                    Japan 0.6567438
## 51:   Oceania                Australia 0.6572847
## 52:    Africa             Burkina Faso 0.6599589
## 53:    Europe                  Croatia 0.6610773
## 54:    Europe                  Romania 0.6627251
## 55:    Europe           United Kingdom 0.6639204
## 56:    Africa                    Libya 0.6666597
## 57:  Americas                Argentina 0.6675349
## 58:      Asia                   Turkey 0.6729158
## 59:  Americas                Venezuela 0.6730108
## 60:    Africa                  Algeria 0.6789910
## 61:      Asia                    Syria 0.6790189
## 62:    Europe                 Portugal 0.6794900
## 63:      Asia                     Iran 0.6814100
## 64:    Africa                    Egypt 0.6817869
## 65:      Asia               Azerbaijan 0.6830715
## 66:      Asia                    China 0.6897170
## 67:      Asia                  Georgia 0.6921287
## 68:  Americas                 Colombia 0.6945741
## 69:  Americas                    Chile 0.6955291
## 70:  Americas                   Mexico 0.6956149
## 71:    Europe                  Moldova 0.6990668
## 72:      Asia              Afghanistan 0.7010588
## 73:      Asia                     Iraq 0.7012100
## 74:      Asia                    India 0.7029295
## 75:    Africa                 Ethiopia 0.7084147
## 76:      Asia              Philippines 0.7161822
## 77:      Asia               Uzbekistan 0.7199820
## 78:    Europe                  Albania 0.7204869
## 79:      Asia               Bangladesh 0.7204869
## 80:      Asia                Indonesia 0.7204869
## 81:      Asia               Kyrgyzstan 0.7204869
## 82:      Asia                    Nepal 0.7204869
## 83:    Africa                  Nigeria 0.7204869
## 84:      Asia              North Korea 0.7204869
## 85:      Asia                 Pakistan 0.7204869
```

```
##  86:     Asia                 Sri Lanka 0.7204869
##  87:   Africa                     Sudan 0.7204869
##  88:     Asia                Tajikistan 0.7204869
##  89:   Africa                  Tanzania 0.7204869
##  90:     Asia                  Thailand 0.7204869
##  91:     Asia              Turkmenistan 0.7204869
##  92:     Asia                   Vietnam 0.7204869
##  93:   Europe Bosnia and Herzegovina 0.7335640
##  94:     Asia                     Burma 0.7335640
##  95:   Africa                  Cameroon 0.7335640
##  96:   Africa                      Chad 0.7335640
##  97:   Africa                     Congo 0.7335640
##  98: Americas                Costa Rica 0.7335640
##  99: Americas             French Guiana 0.7335640
## 100:   Africa                     Gabon 0.7335640
## 101:   Africa                     Ghana 0.7335640
## 102: Americas                 Guatemala 0.7335640
## 103: Americas                   Jamaica 0.7335640
## 104:   Africa                     Kenya 0.7335640
## 105:   Africa                   Lesotho 0.7335640
## 106:     Asia                  Mongolia 0.7335640
## 107:   Africa                   Morocco 0.7335640
## 108:  Oceania               New Zealand 0.7335640
## 109: Americas                    Panama 0.7335640
## 110:  Oceania          Papua New Guinea 0.7335640
## 111: Americas                  Paraguay 0.7335640
## 112:   Europe                    Poland 0.7335640
## 113:   Europe                    Serbia 0.7335640
## 114:   Africa                      Togo 0.7335640
## 115: Americas                  Trinidad 0.7335640
## 116: Americas                   Uruguay 0.7335640
## 117:   Africa            Western Sahara 0.7335640
## 118:   Africa                     Zaire 0.7335640
## 119: Americas                    Belize 0.7339335
## 120: Americas               El Salvador 0.7369390
## 121:     Asia                   Armenia 0.7374656
## 122: Americas               Puerto Rico 0.7413326
## 123: Americas                   Bolivia 0.7433014
## 124:   Africa                    Uganda 0.7555268
## 125:   Africa                Mauritania 0.7593394
## 126:   Africa                    Guinea 0.7594368
## 127:   Europe                 Macedonia 0.7596352
## 128:     Asia                  Malaysia 0.7605567
## 129: Americas                      Peru 0.7611599
## 130: Americas                  Suriname 0.7618812
## 131:   Africa                   Senegal 0.7670757
## 132: Americas                 Nicaragua 0.7680709
## 133:     Asia                     Yemen 0.7681130
```

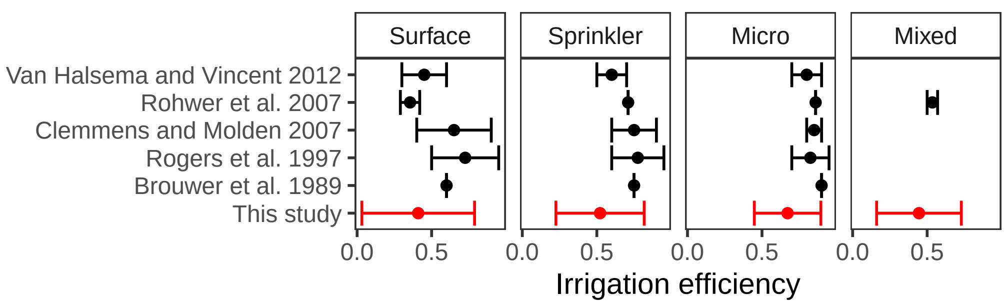
```
## 134:    Africa                Madagascar 0.7682063
## 135:    Africa                      Mali 0.7685685
## 136:    Africa                    Angola 0.7690661
## 137:      Asia                    Bhutan 0.7690661
## 138:    Africa                   Burundi 0.7690661
## 139:      Asia                  Cambodia 0.7690661
## 140:    Africa Central African Republic 0.7690661
## 141:    Africa                  Djibouti 0.7690661
## 142:  Americas        Dominican Republic 0.7690661
## 143:    Africa         Equatorial Guinea 0.7690661
## 144:    Africa                   Eritrea 0.7690661
## 145:    Africa                    Gambia 0.7690661
## 146:    Africa             Guinea-Bissau 0.7690661
## 147:  Americas                    Guyana 0.7690661
## 148:  Americas                     Haiti 0.7690661
## 149:  Americas                  Honduras 0.7690661
## 150:      Asia                      Laos 0.7690661
## 151:    Africa                   Liberia 0.7690661
## 152:    Africa                     Niger 0.7690661
## 153:    Europe                    Norway 0.7690661
## 154:    Africa                    Rwanda 0.7690661
## 155:    Africa              Sierra Leone 0.7690661
## 156:    Africa                   Somalia 0.7690661
## 157:      Asia               South Korea 0.7690661
## 158:      Asia                      Oman 0.7883613
##       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`.
```



```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()
```




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

dd <- uncertainty.dt[!Continent == "Oceania"][Study == "One IFT per country"] %>%
  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
```

```
## named list()
```

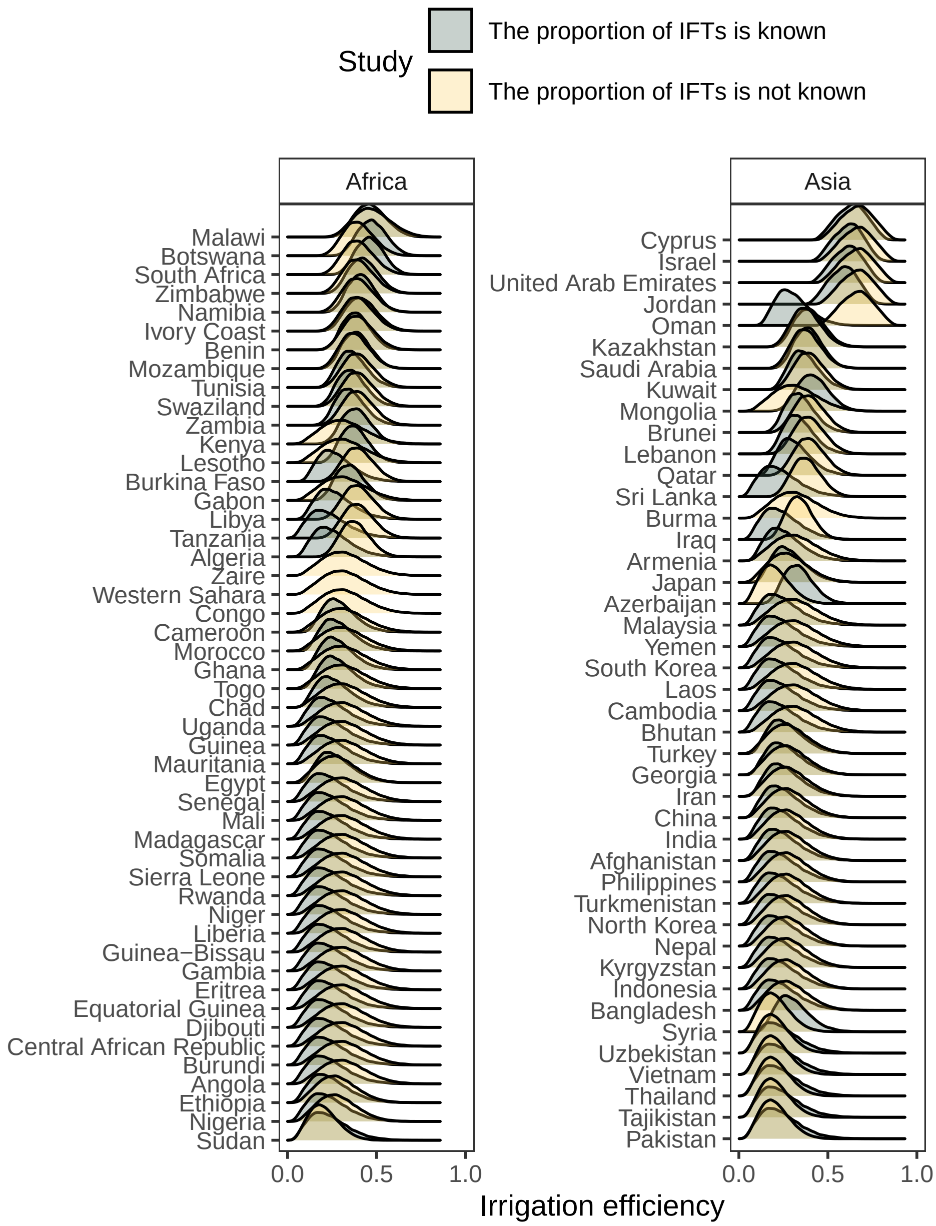
```r
ff <- uncertainty.dt[!Continent == "Oceania"] %>%
  split(., .$Approach, drop = TRUE)
```

3 Uncertainty analysis

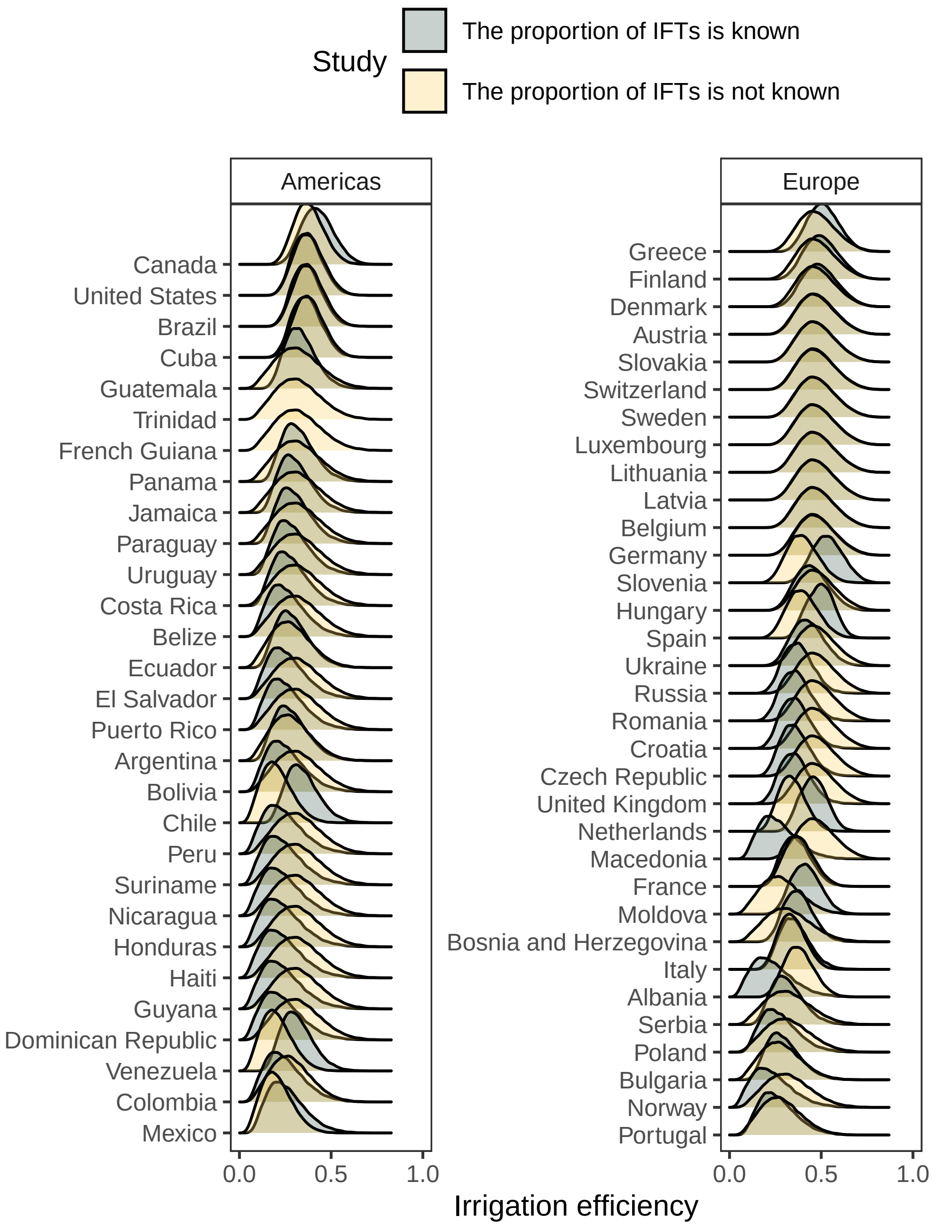
```r
# PLOT UNCERTAINTY ---------------------------------------------------------------

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

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

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

gg
```

```
## [[1]]

## Picking joint bandwidth of 0.0132

## Picking joint bandwidth of 0.0126
```



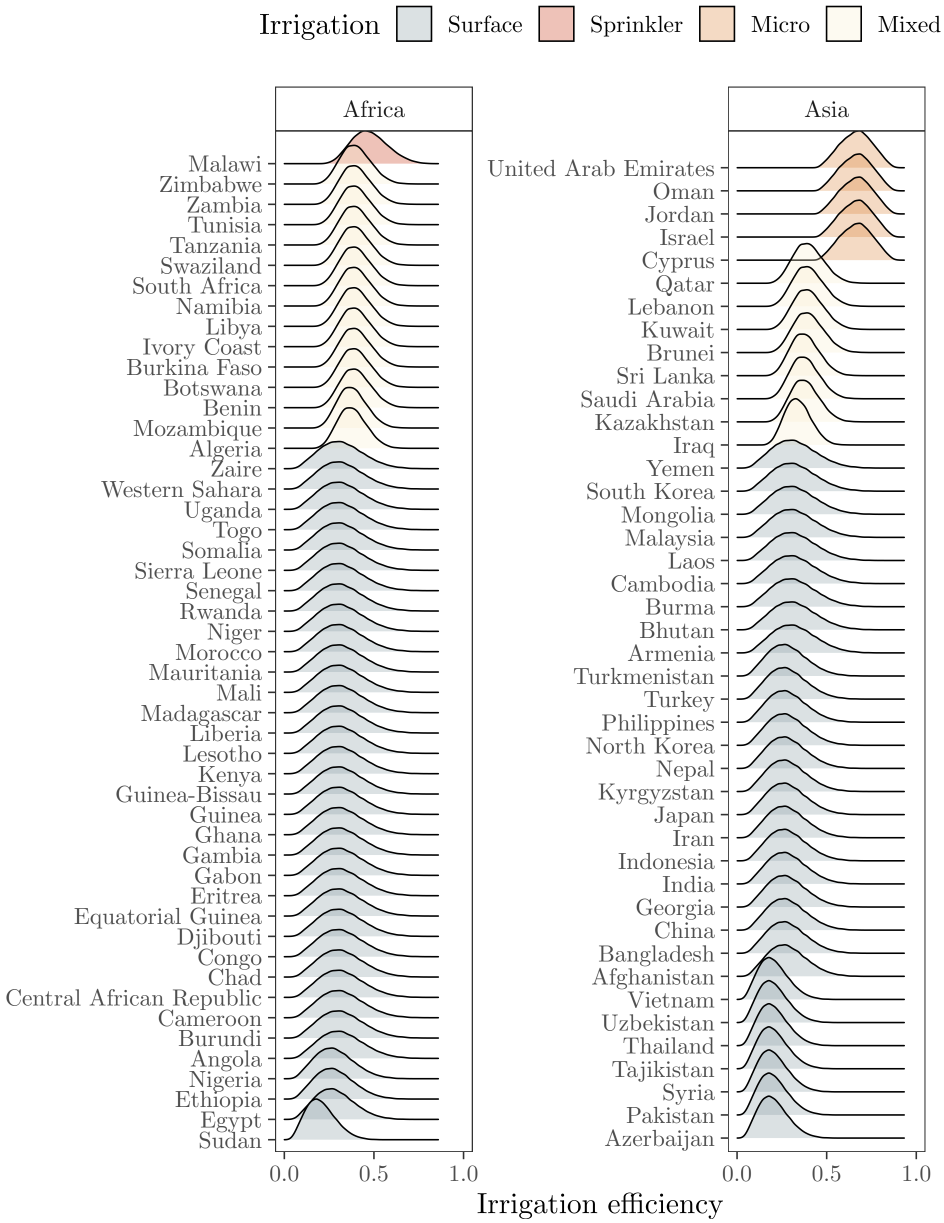

```
##
## [[2]]

## Picking joint bandwidth of 0.0132

## Picking joint bandwidth of 0.0121
```




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

gg <- list()

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

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

gg
```

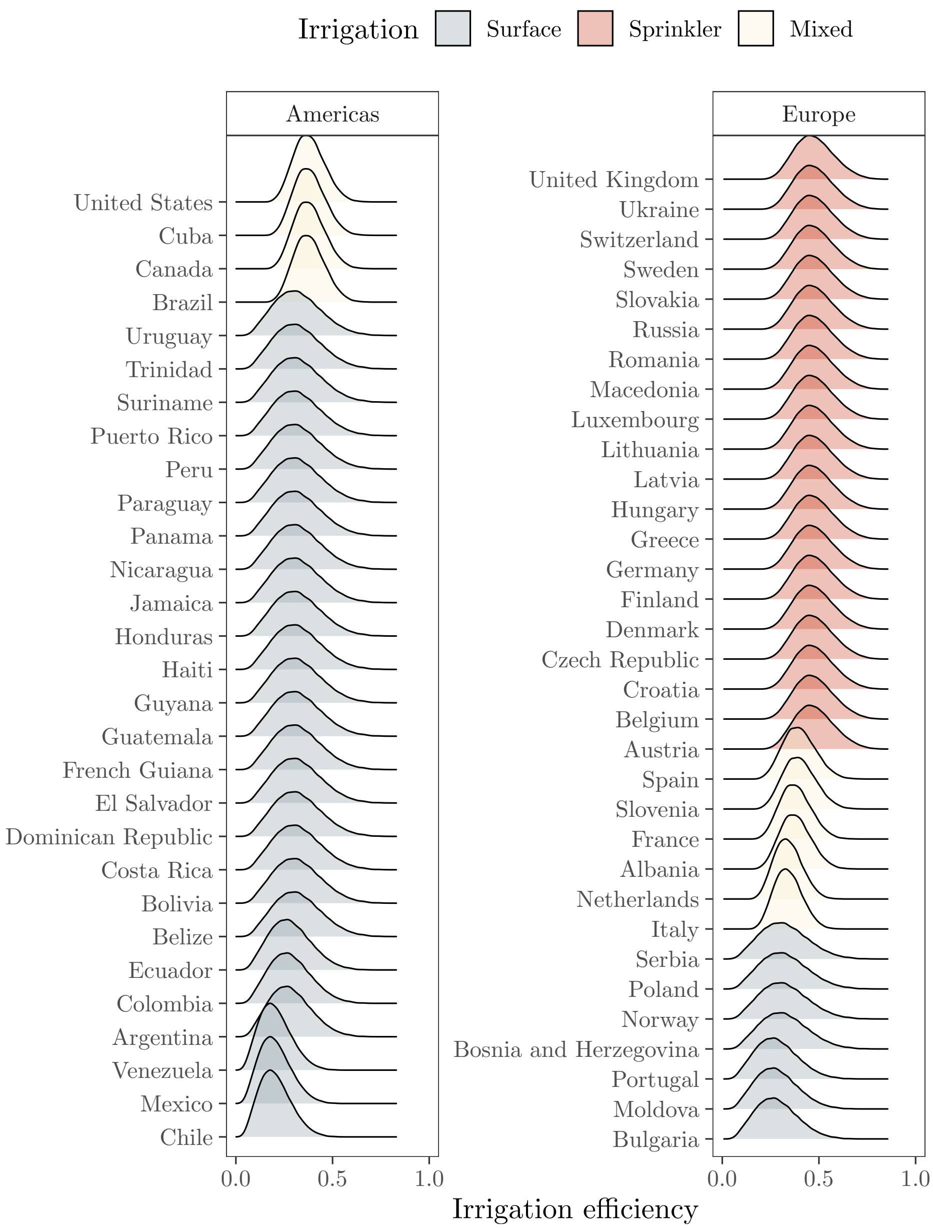
```
## [[1]]

## Picking joint bandwidth of 0.0138

## Picking joint bandwidth of 0.0126
```




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

```
## Picking joint bandwidth of 0.014
```

```
## Picking joint bandwidth of 0.0127
```



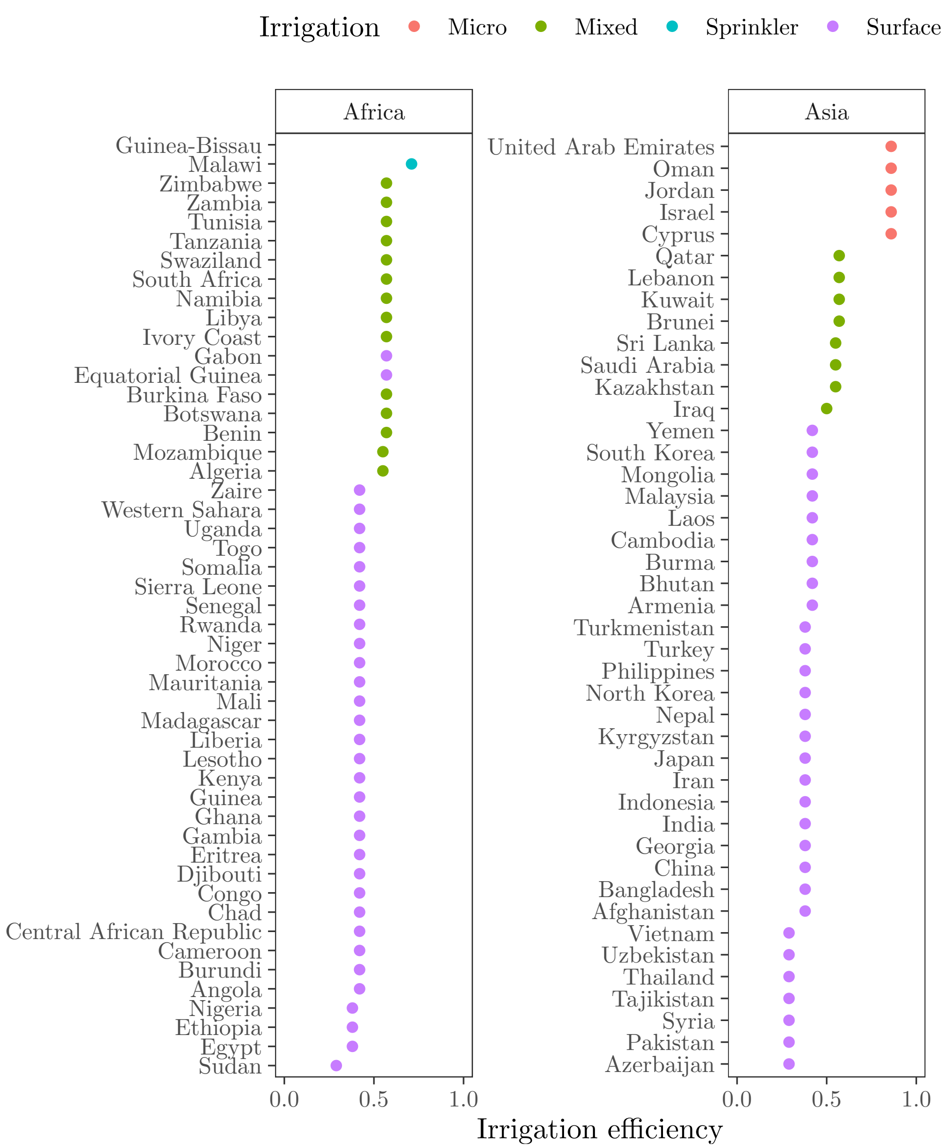

```
# PLOT ROHWER ET AL.'S IRRIGATION EFFICIENCY VALUES ---------------------------------

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

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

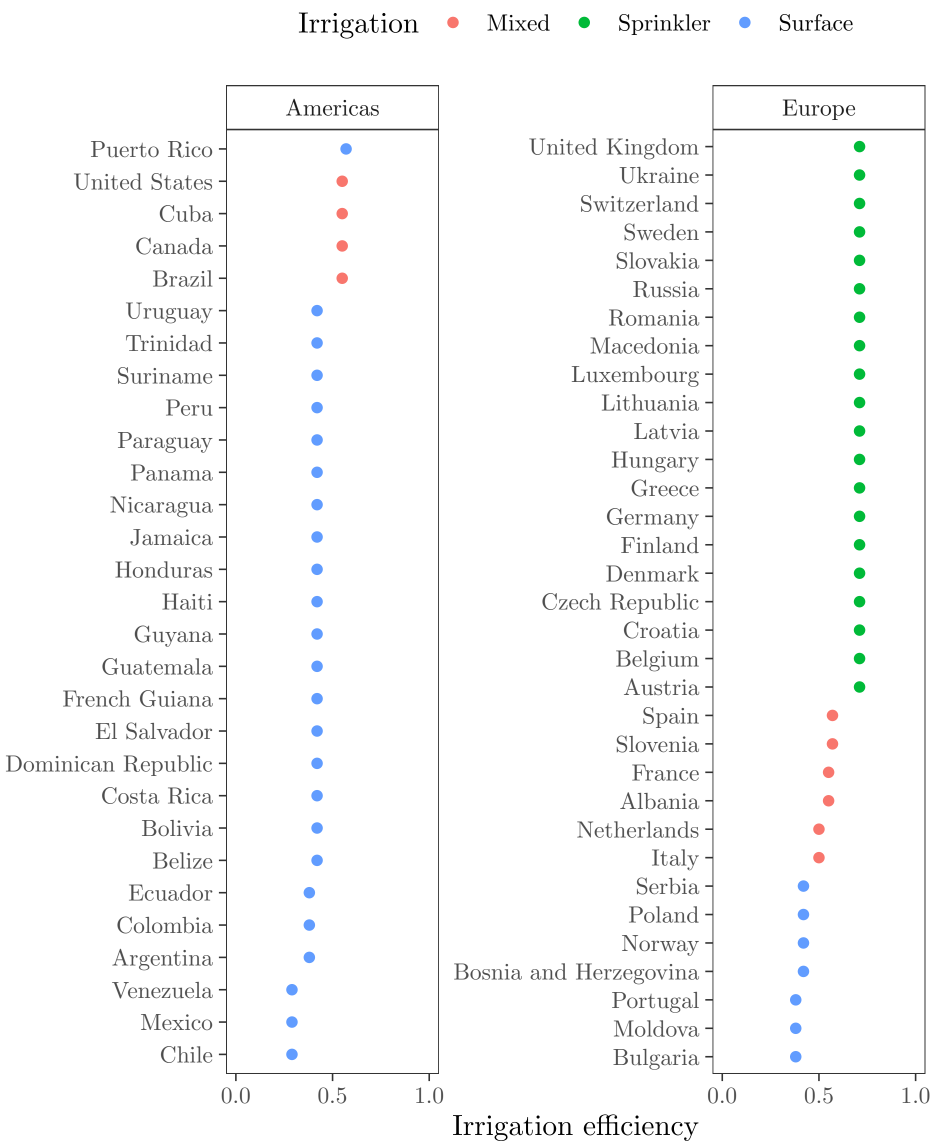
```
dd <- list()
for (i in 1:length(list_continents)) {
  dd[[i]] <- ggplot(rohwer[Continent %in% list_continents[[i]]],
                    aes(x = Ep, y = fct_reorder(Country, Ep), color = IFT)) +
    geom_point() +
    labs(x = "Irrigation efficiency", y = "") +
    scale_x_continuous(breaks = pretty_breaks(n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

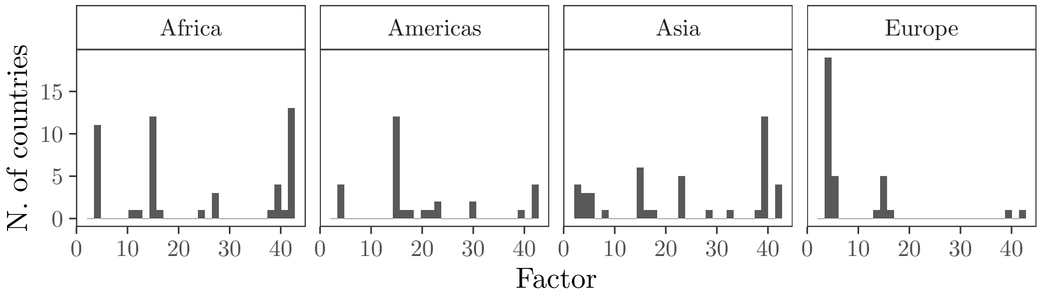



```
##
## [[2]]
```




```
# 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`.
```




```
# 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               16
##  3:      4               24
##  4:      5                5
##  5:      8                1
##  6:     10                1
##  7:     11                1
##  8:     14               26
##  9:     15               12
## 10:     16                2
## 11:     17                1
## 12:     18                1
## 13:     20                1
## 14:     22                4
## 15:     23                4
## 16:     24                1
## 17:     27                3
## 18:     28                1
## 19:     29                1
## 20:     30                1
## 21:     32                1
## 22:     37                2
## 23:     38               15
## 24:     39                3
## 25:     40                1
## 26:     41               22
##     factor number.countries
```

3.1 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",
```

```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)) %>%
```

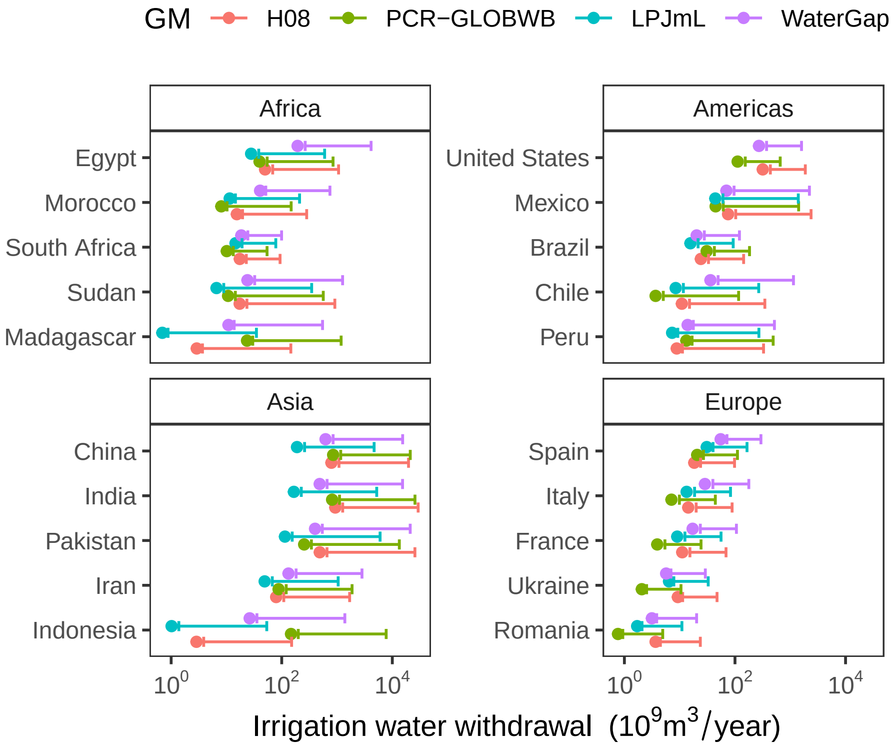
```r
  rbindlist(., idcol = "Model") %>%
  na.omit() %>%
  # To correct for duplicate country in Cyprus
  .[, .(Water.Withdrawn = mean(Water.Withdrawn)), .(Model, Country, Continent, Code)]

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")

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)
```

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

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")

gm.dt[Country %in% countries_list] %>%
  ggplot(., aes(reorder(Country, IWW), IWW, color = Model)) +
  geom_point(position = position_dodge(0.7)) +
  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_discrete(name = "GM") +
  labs(y = expression(paste("Irrigation water withdrawal ", " ", "(", 10^9, m^3/year, "", ")")),
       x = "") +
  facet_wrap(~Continent, scales = "free_y") +
```

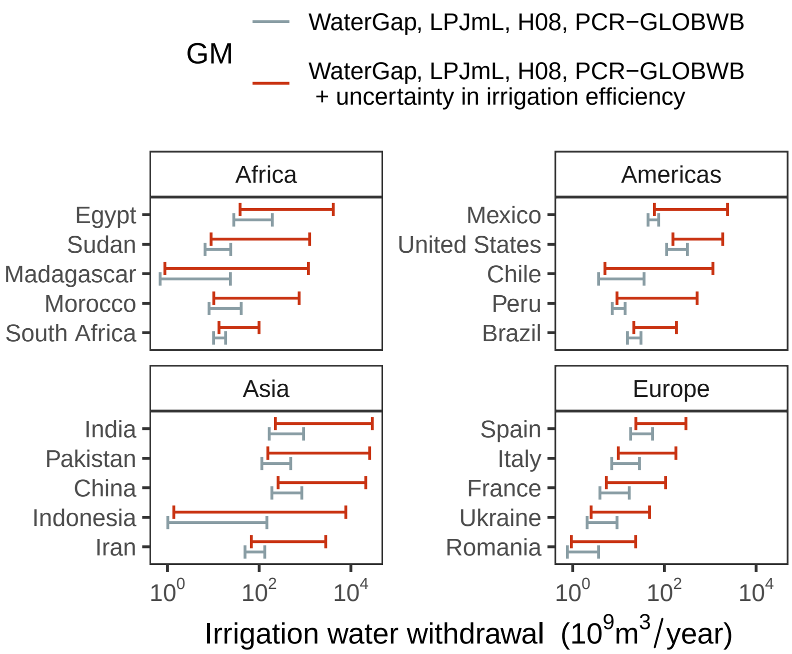
```
  coord_flip() +
  theme_AP()
```

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




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

range.gm <- gm.dt %>%
  .[, .(min = min(IWW, na.rm = TRUE), max = max(IWW, na.rm = TRUE)), .(Country, Continent)] %>%
  .[, Approach:= "WaterGap, LPJmL, H08, PCR-GLOBWB"]

range.study <- gm.dt %>%
  .[, .(min = min(min, na.rm = TRUE), max = max(max, na.rm = TRUE)), .(Country, Continent)] %>%
  .[, Approach:= "WaterGap, LPJmL, H08, PCR-GLOBWB \n + uncertainty in irrigation efficiency"]

rbind(range.gm, range.study) %>%
  .[Country %in% countries_list] %>%
  .[, mean:= (min + max) / 2] %>%
  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("Royal1")) +
  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 = 2, byrow = TRUE))
```




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

dd <- list()
for (i in 1:length(list_continents)) {
  dd[[i]] <- rbind(range.gm, range.study) %>%
    .[, mean:= (min + max) / 2] %>%
    .[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("Royal1")) +
    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 = 2, byrow = TRUE))
}
```

```
dd
```

```
## [[1]]

## Warning: Transformation introduced infinite values in continuous y-axis

## Warning: Transformation introduced infinite values in continuous y-axis

## Warning: Transformation introduced infinite values in continuous y-axis
```


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

## Warning: Transformation introduced infinite values in continuous y-axis
```

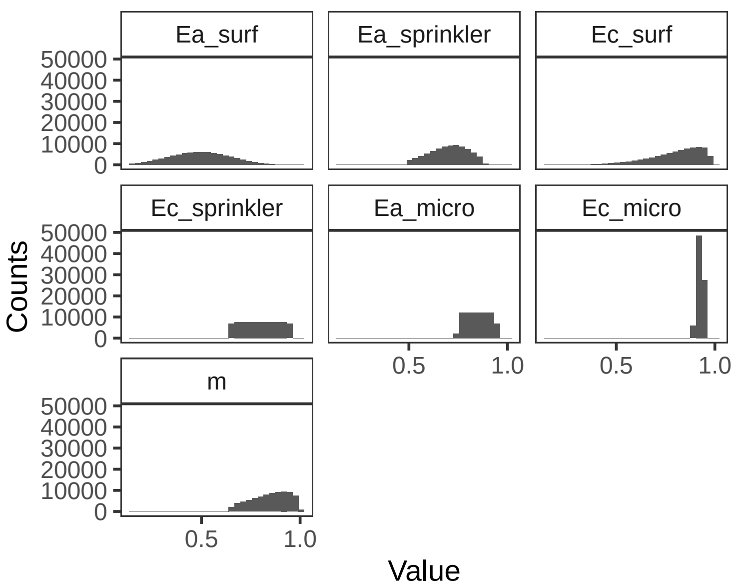

```
# PRINT RANGES -----------------------------------------------------------------

# print(range.study, n = Inf)
```

4 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]

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`.
```



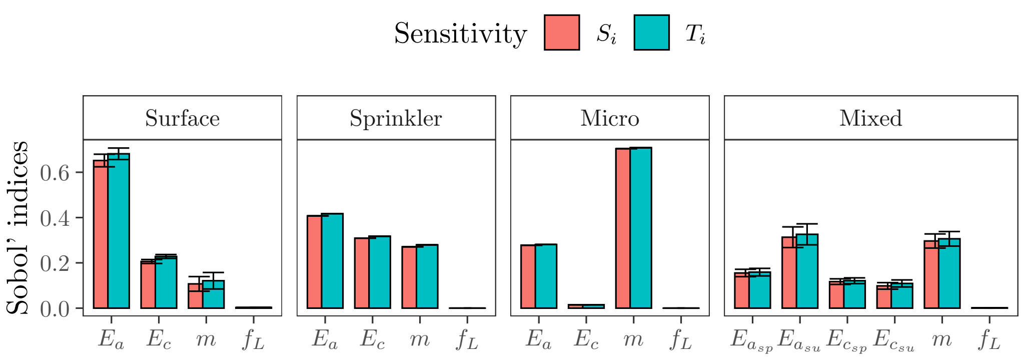

```
# EXTRACT SOBOL' INDICES ------------------------------------------------------------

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)
```

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

```r
# 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 == "I
                                                                               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()
```




```r
# 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",
```

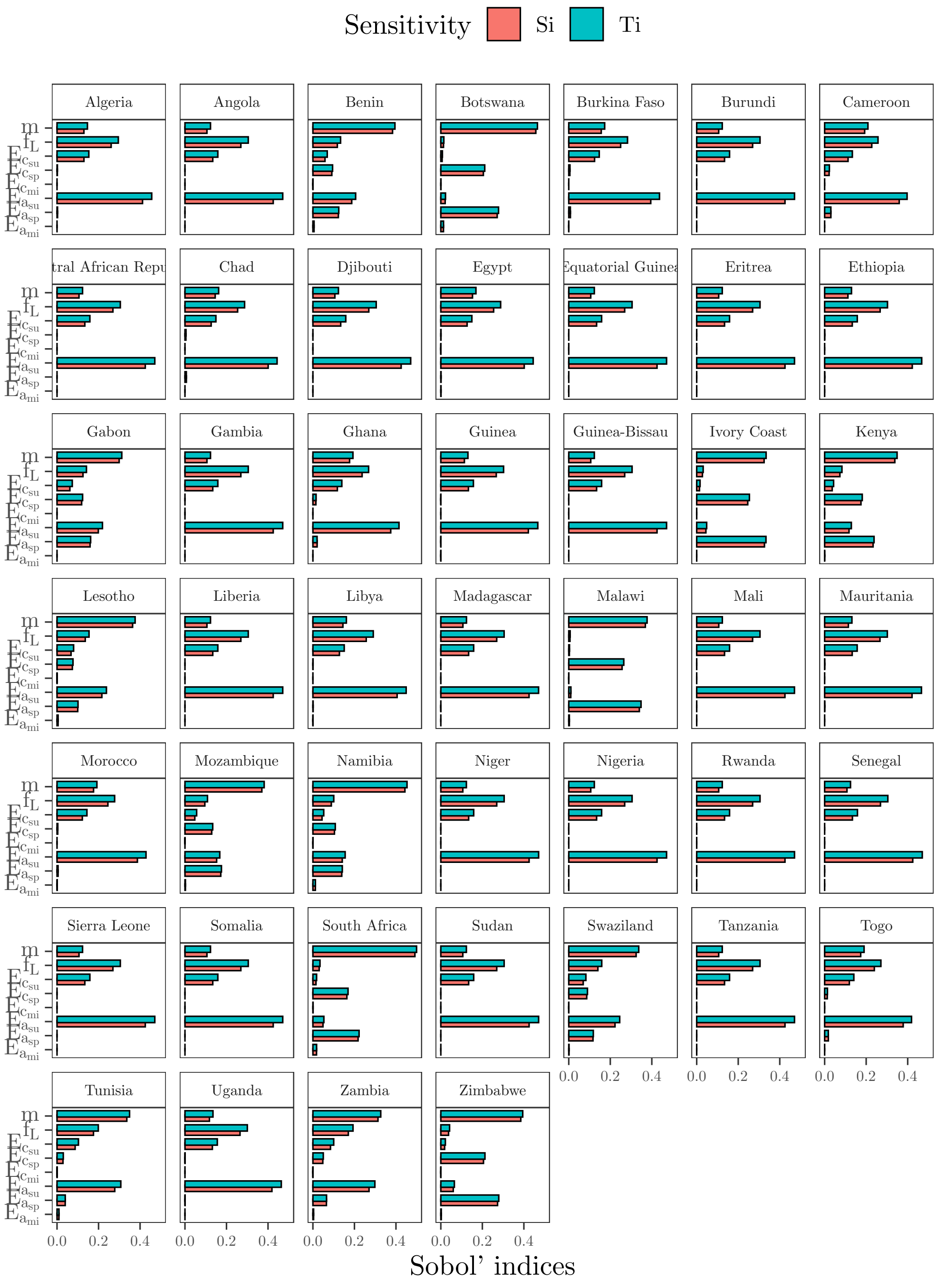
```
                              destination = "continent")] %>%
  .[, parameters:= ifelse(parameters == "Ea_surf", "E[a[su]]",
                          ifelse(parameters == "Ec_surf", "E[c[su]]",
                                 ifelse(parameters == "Ea_sprinkler", "E[a[sp]]",
                                        ifelse(parameters == "Ec_sprinkler", "E[c[sp]]",
                                               ifelse(parameters == "Ea_micro", "E[a[mi]]",
                                                      ifelse(parameters == "Ec_micro", "E[c[mi]]
                                                             ifelse(parameters == "Proportion_la
```

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

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

lapply(Continent_vector, function(x)
  ggplot(jager.ind[Continent == x], aes(parameters, original, fill = sensitivity), color = blac
    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)
)
```

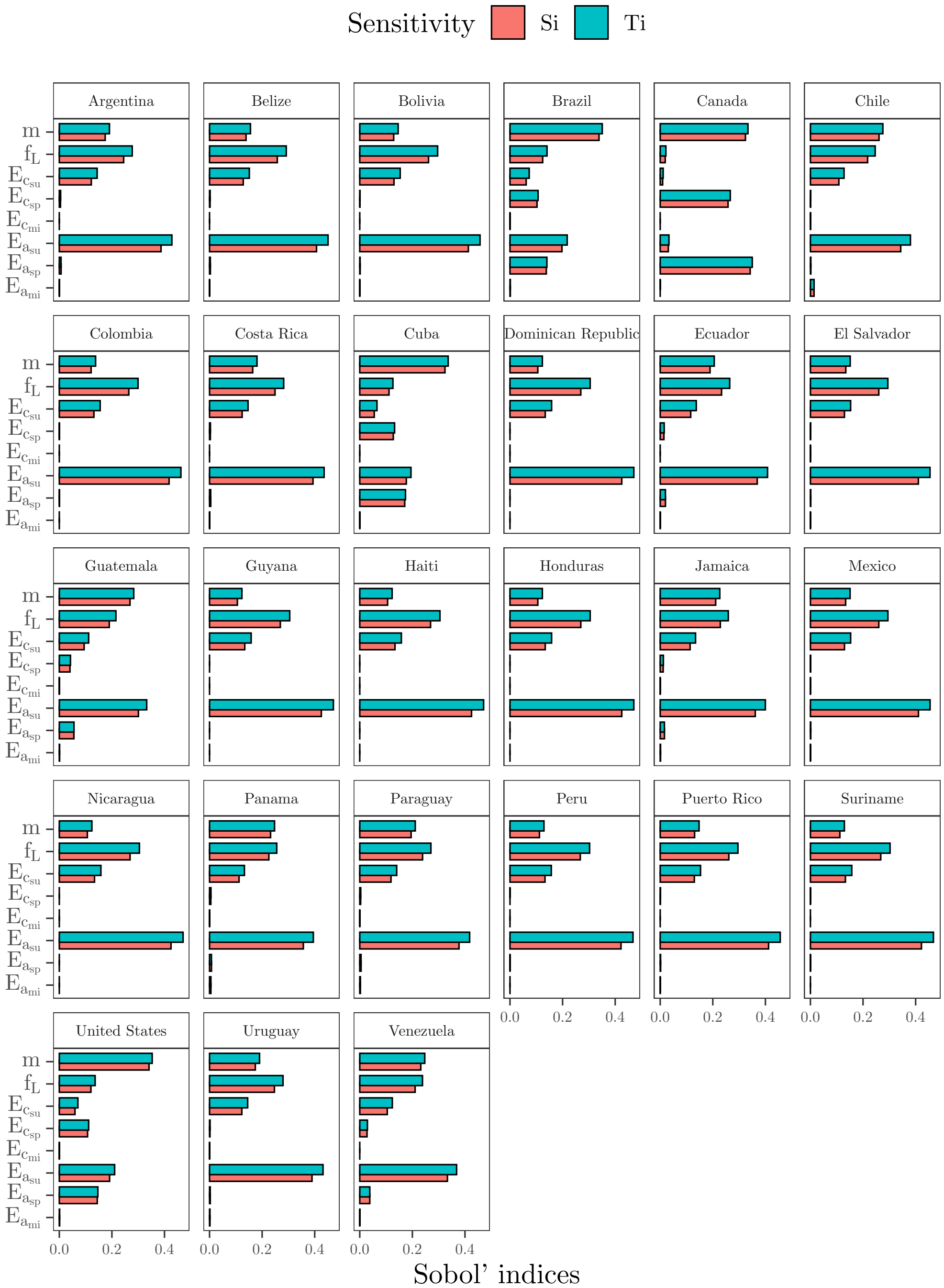
```
## [[1]]
```

Africa


Sensitivity
Si
Ti
Algeria
Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
tral African Repu
Chad
Djibouti
Egypt
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Gambia
Ghana
Guinea
Guinea-Bissau
Ivory Coast
Kenya
Lesotho
Liberia
Libya
Madagascar
Malawi
Mali
Mauritania
Morocco
Mozambique
Namibia
Niger
Nigeria
Rwanda
Senegal
Sierra Leone
Somalia
South Africa
Sudan
Swaziland
Tanzania
Togo
Tunisia
Uganda
Zambia
Zimbabwe
m
f_L
$E_{c_{su}}$
$E_{c_{sp}}$
$E_{c_{mi}}$
$E_{a_{su}}$
$E_{a_{sp}}$
$E_{a_{mi}}$
0.0
0.2
0.4
Sobol' indices

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

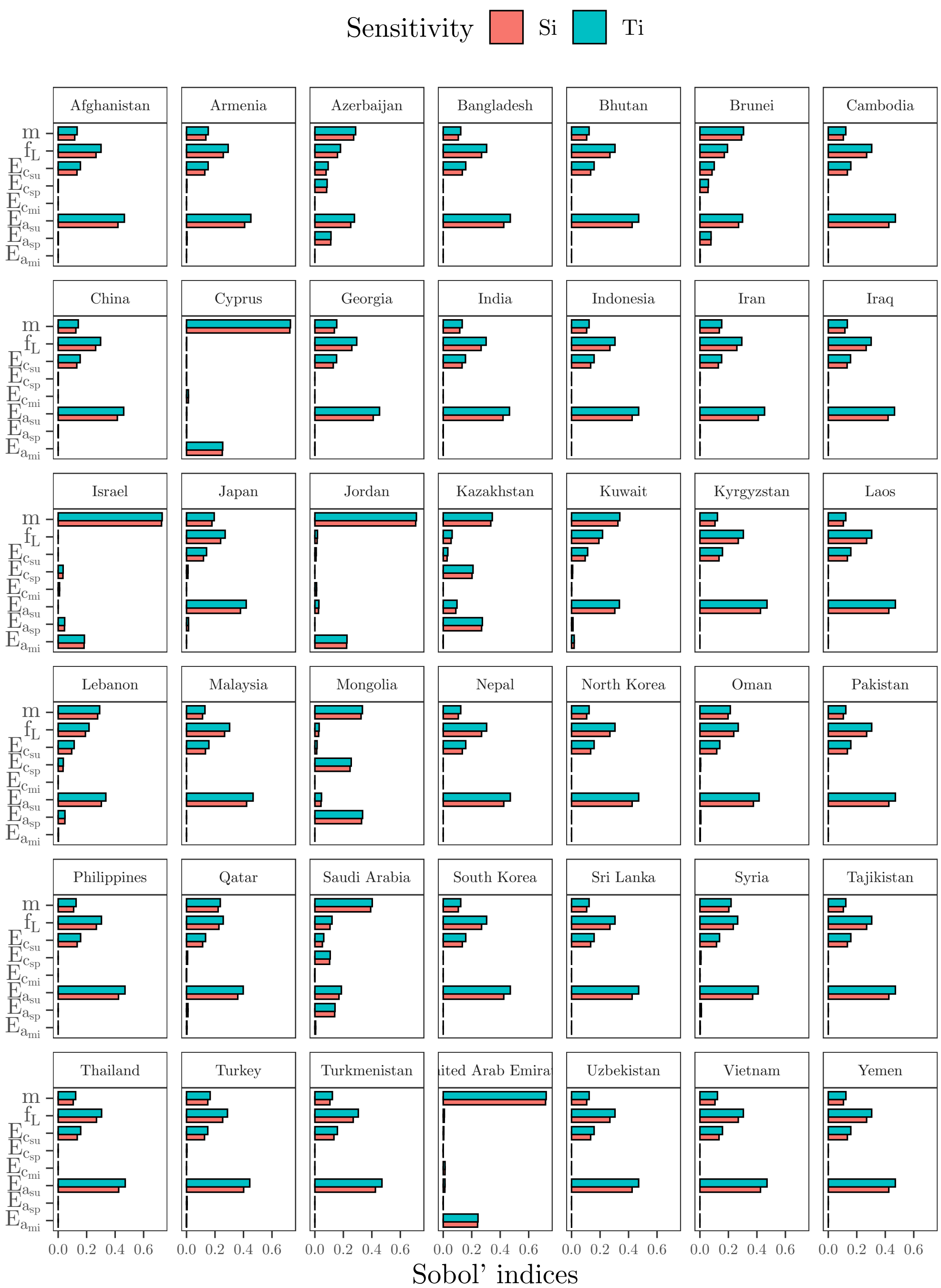
Americas



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
m
f_L
$E_{c_{su}}$
$E_{c_{sp}}$
$E_{c_{mi}}$
$E_{a_{su}}$
$E_{a_{sp}}$
$E_{a_{mi}}$
0.0
0.2
0.4
Sobol' indices

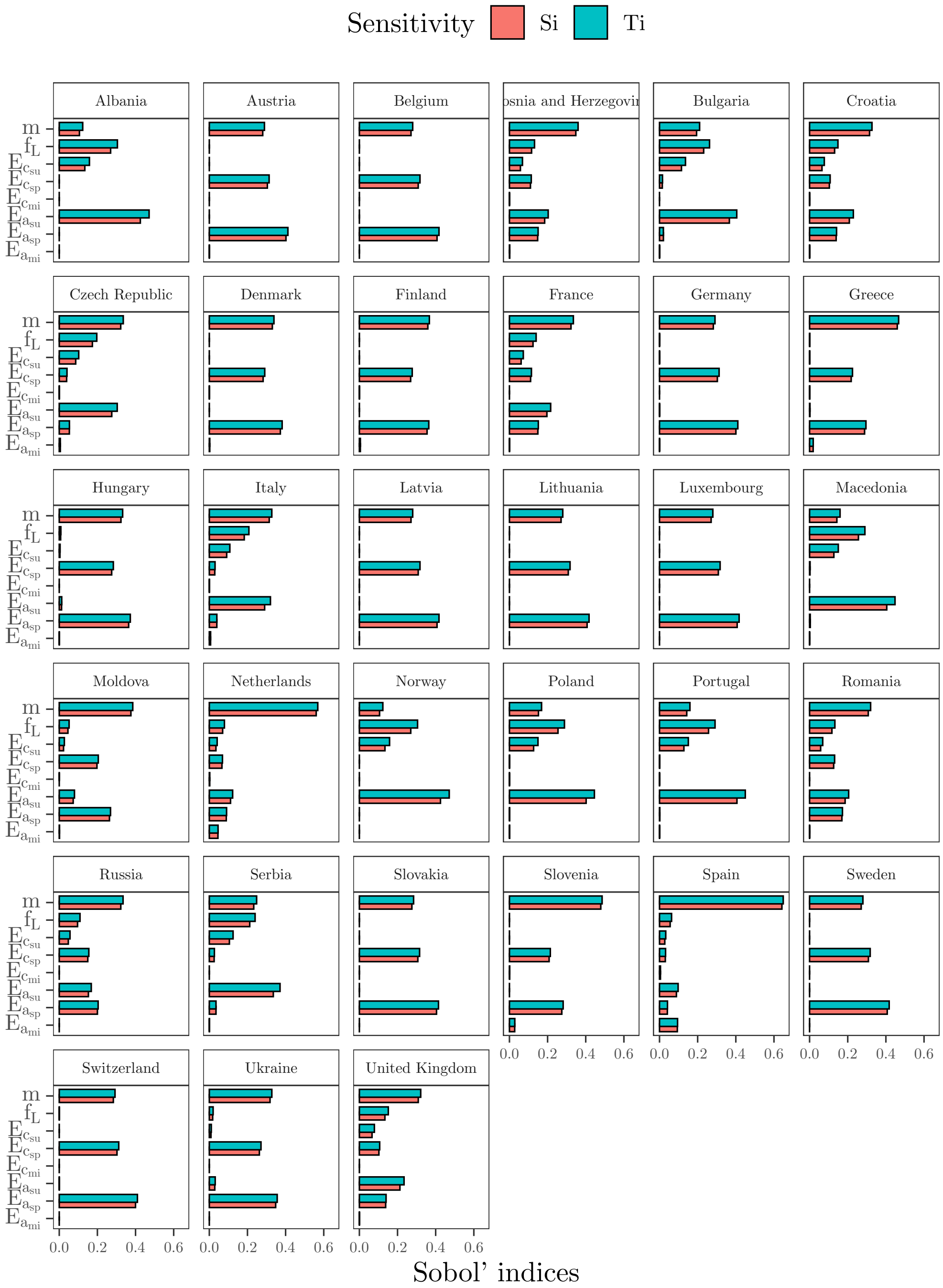

```
##
## [[3]]
```

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 Emira
Uzbekistan
Vietnam
Yemen
m
f_L
$E_{c_{su}}$
$E_{c_{sp}}$
$E_{c_{mi}}$
$E_{a_{su}}$
$E_{a_{sp}}$
$E_{a_{mi}}$
0.0 0.2 0.4 0.6
Sobol' indices

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

Europe


Sensitivity
Si
Ti
Albania
Austria
Belgium
osnia and Herzegovi
Bulgaria
Croatia
Czech Republic
Denmark
Finland
France
Germany
Greece
Hungary
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Moldova
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
Spain
Sweden
Switzerland
Ukraine
United Kingdom
m
f_L
$E_{c_{su}}$
$E_{c_{sp}}$
$E_{c_{mi}}$
$E_{a_{su}}$
$E_{a_{sp}}$
$E_{a_{mi}}$
0.0
0.2
0.4
0.6
Sobol' indices