Uncertainty in global irrigation water use persists after 50 years of research

R code

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Contents

1 Preliminary functions

```
#   PRELIMINARY FUNCTIONS ###########################################################

sensobol::load_packages(c("openxlsx", "data.table", "tidyverse","cowplot",
                          "benchmarkme", "parallel", "wesanderson", "scales", "ncdf4",
                          "countrycode", "rworldmap", "sp", "doParallel", "here", "lme4",
                          "microbenchmark", "mgcv", "brms", "randomForest", "here"))

# 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),
          strip.background = element_rect(fill = "white"),
          legend.text = element_text(size = 7.3),
          axis.title = element_text(size = 10),
          legend.key.width = unit(0.4, "cm"),
          legend.key.height = unit(0.4, "cm"),
          legend.key.spacing.y = unit(0, "lines"),
          legend.box.spacing = unit(0, "pt"),
          legend.title = element_text(size = 7.3),
          axis.text.x = element_text(size = 7),
          axis.text.y = element_text(size = 7),
          axis.title.x = element_text(size = 7.3),
          axis.title.y = element_text(size = 7.3),
          plot.title = element_text(size = 8),
          strip.text.x = element_text(size = 7.4),
          strip.text.y = element_text(size = 7.4))
}

# Select color palette ---------------------------------------------------------

selected.palette <- "Darjeeling1"
```

```
# SOURCE ALL R FUNCTIONS NEEDED FOR THE STUDY ######################################

# Source all .R files in the "functions" folder --------------------------------

r_functions <- list.files(path = here("functions"), pattern = "\\.R$", full.names = TRUE)
lapply(r_functions, source)
```

2 Bibliographical study

```
# NAOMI DATASET ###################################################################

references.projected <- data.table(read.xlsx("./data/references_projection.xlsx")) %>%
  .[, focus:= "projected"]

references.current <- data.table(read.xlsx("./data/references_current.xlsx")) %>%
  .[, focus:= "current"]

references.full.dt <- rbind(references.projected, references.current) %>%
  .[, study:= paste(author, model, climate.scenario, sep = ".")]

# CLEAN THE DATASET ###############################################################

colnames_vector <- c("title", "author", "region")

# Remove leading and trailing spaces ------------------------------------------

references.full.dt[, (colnames_vector):= lapply(.SD, trimws), .SDcols = (colnames_vector)]
references.full.dt[, (colnames_vector):= lapply(.SD, str_squish), .SDcols = (colnames_vector)]

# Lowercaps -------------------------------------------------------------------

references.full.dt[, (colnames_vector):= lapply(.SD, tolower), .SDcols = (colnames_vector)]

# Remove multiple spaces ------------------------------------------------------

references.full.dt[, (colnames_vector):= lapply(.SD, function(x)
  gsub("\\s+", " ", x)), .SDcols = (colnames_vector)]

# Correct America -------------------------------------------------------------

references.full.dt[, region:= ifelse(region == "america", "americas", region)]

# Extract the publication year ------------------------------------------------

references.full.dt[, publication.date:= str_extract(author, "\\d{4}")] %>%
  .[, publication.date:= as.numeric(publication.date)]
```

```
# FEATURES OF THE DATASET #########################################################

# Definition of target years --------------------------------------------------

target_year <- c(2010, 2050, 2070, 2100)

# Name of different studies ---------------------------------------------------
```

```r
sort(unique(references.full.dt[variable == "iww" & region == "global", title]))
```

```
##  [1] "a global water scarcity assessment under shared socio-economic pathways - part 2: wate
##  [2] "a pathway of global food supply adaptation in a world with increasingly constrained gr
##  [3] "agricultural green and blue water consumption and its influence on the global water sy
##  [4] "an estimation of global virtual water flow and sources of water withdrawal for major c
##  [5] "an integrated assessment of global and regional water demands for electricity generati
##  [6] "an interpreted model for the assessment of global water resources - part 2: applicatio
##  [7] "appraisal and assessment of world water resources"
##  [8] "aquastat: fao's global information system on water and agriculture"
##  [9] "climate change impacts on irrigation water requirements: effects of mitigation, 1990-2
## [10] "climate impacts on global irrigation requirements under 19 gcms, simulated with a vege
## [11] "climate policy implications for agricultural water demand"
## [12] "future long-term changes in global water resources driven by socio-economic and climat
## [13] "global and regional evaluation of energy for water"
## [14] "global impacts of conversions from natural to agricultural ecosystems on water resourc
## [15] "global irrigation characteristics and effects simulated by fully coupled land surface
## [16] "global irrigation water demand: variability and uncertainties arising from agricultura
## [17] "global modeling of irrigation water requirements"
## [18] "global modeling of withdrawal, allocation and consumptive use of surface water and gro
## [19] "global monthly sectoral water use for 2010-2100 at 0.5° resolution across alternative
## [20] "global water demand and supply projections"
## [21] "globwat - a global water balance model to assess water use in irrigated agriculture"
## [22] "how can we cope with the water resources situation by the year 2050?"
## [23] "human appropriation of renewable fresh water"
## [24] "impact of climate forcing uncertainty and human water use on global and continental wa
## [25] "implementation and evaluation of irrigation techniques in the community land model"
## [26] "incorporating anthropogenic water regulation modules into a land surface model"
## [27] "incorporation of groundwater pumping in a global land surface model with the represent
## [28] "isimip database"
## [29] "long-term global water projections using six socioeconomic scenarios in an intgrated a
## [30] "modelling global water stress of the recent past: on the relative importance of trends
## [31] "multimodel projections and uncertainties of irrigation water demand under climate char
## [32] "pcr-globwb 2: a 5 arcmin global hydrological and water resources model"
## [33] "quantifying global agricultural water appropriation with data derived from earth obser
## [34] "recent global cropland water consumption constrained by observations"
## [35] "reconciling irrigated food production with environmental flows for sustainable develop
## [36] "reconstructing 20th century global hydrography: a contribution to the global terrestri
## [37] "the state of the world's land and water resources for food and agriculture"
## [38] "the world's water, 2000-2001: the biennial report on freshwater resources"
## [39] "water 2050. moving toward a sustainable vision fot the earth's fresh water"
## [40] "water and sustainability. global pattern and long-range problems"
## [41] "world agriculture towards 2030/2055"
## [42] "world water demand and supply, 1990 to 2025: scenarios and issues"
## [43] "world water in 2025 - global modeling and scenario analysis for the world commission o
## [44] "world water resources and their future"
```

```r
# Number of data points ------------------------------------------------------

nrow(references.full.dt[variable == "iww" & region == "global"])
```

```
## [1] 1209
```

```r
# Number of different studies per variable -----------------------------------

references.full.dt[region == "global", unique(title), variable] %>%
  .[, .N, variable]
```

```
##    variable     N
##      <char> <int>
## 1:      iww    45
## 2:      tww    27
## 3:      iwc    17
## 4:      twc     6
## 5:      iwr     2
```

```r
# Number of data points for 2000, 2050, 2070, 2100 ---------------------------

references.full.dt[variable == "iww" & region == "global" &
                     estimation.year %in% target_year, .N, estimation.year]
```

```
##    estimation.year     N
##              <num> <int>
## 1:            2070   119
## 2:            2100   106
## 3:            2010   101
## 4:            2050    98
```

```r
# Number of unique studies estimating for 2000, 2050, 2070, 2100 -------------

references.full.dt[variable == "iww" & region == "global" &
                     estimation.year %in% target_year, unique(title), estimation.year] %>%
  .[, .N, estimation.year]
```

```
##    estimation.year     N
##              <num> <int>
## 1:            2070     4
## 2:            2100     3
## 3:            2010     6
## 4:            2050     7
```

```r
# Number of data points for every targeted year ------------------------------

references.full.dt[variable == "iww" & region == "global", .N, estimation.year] %>%
  .[order(estimation.year)]
```

```
##     estimation.year     N
##               <num> <int>
```

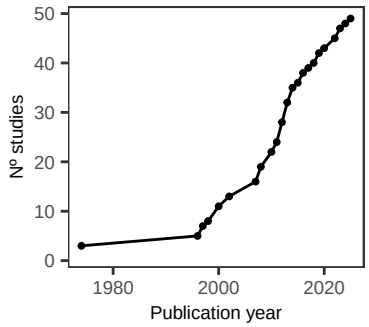
```
##  1:             1900     2
##  2:             1910     1
##  3:             1920     1
##  4:             1930     1
##  5:             1940     3
##  6:             1950     3
##  7:             1960     4
##  8:             1970     4
##  9:             1975    22
## 10:             1980    27
## 11:             1983     1
## 12:             1985    26
## 13:             1990    26
## 14:             1994     6
## 15:             1995    38
## 16:             1996     2
## 17:             2000    60
## 18:             2002     2
## 19:             2003     1
## 20:             2004     1
## 21:             2005    19
## 22:             2006     2
## 23:             2008     1
## 24:             2010   101
## 25:             2015     3
## 26:             2020    84
## 27:             2021     1
## 28:             2025     6
## 29:             2030    82
## 30:             2040    93
## 31:             2050    98
## 32:             2055     2
## 33:             2060    82
## 34:             2070   119
## 35:             2075     2
## 36:             2080    91
## 37:             2090    79
## 38:             2095     7
## 39:             2100   106
##     estimation.year     N
```

```r
# Cumulative sum of published studies ----------------------------------------

cumulative.iww <- references.full.dt[, .(title, publication.date, variable)] %>%
  .[variable == "iww"] %>%
  .[!duplicated(.)] %>%
  setorder(., publication.date) %>%
  .[, .N, publication.date] %>%
```

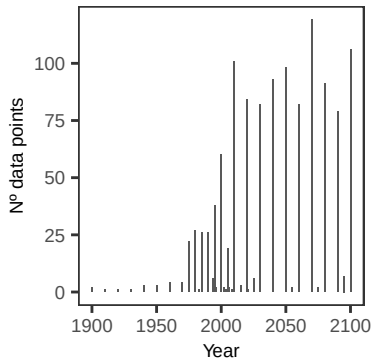
```
  .[, cumulative_sum := cumsum(N)] %>%
  ggplot(., aes(publication.date, cumulative_sum)) +
  geom_line() +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  geom_point(size = 0.7) +
  theme_AP() +
  labs(x = "Publication year", y = "Nº studies")

cumulative.iww
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_line()`).
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_point()`).
```

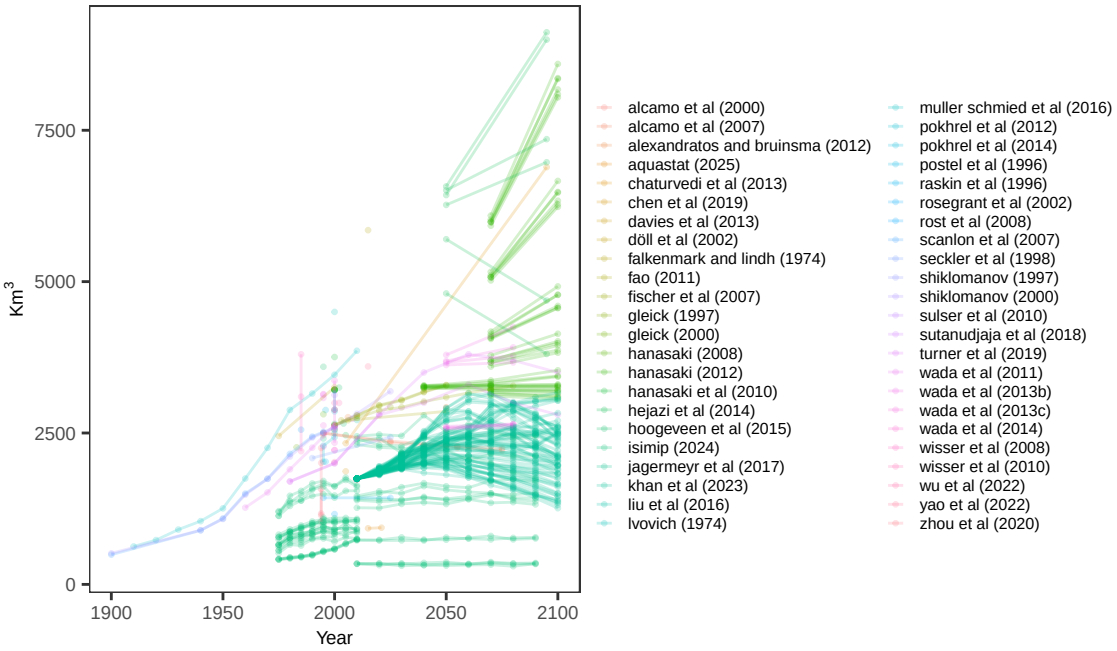



```
# DISTRIBUTION OF DATA POINTS THROUGH YEARS @####################################

references.full.dt[variable == "iww" & region == "global", .N, estimation.year] %>%
  ggplot(., aes(estimation.year, N)) +
  geom_bar(stat = "identity") +
  labs(x = "Year", y = "Nº data points") +
  theme_AP()
```

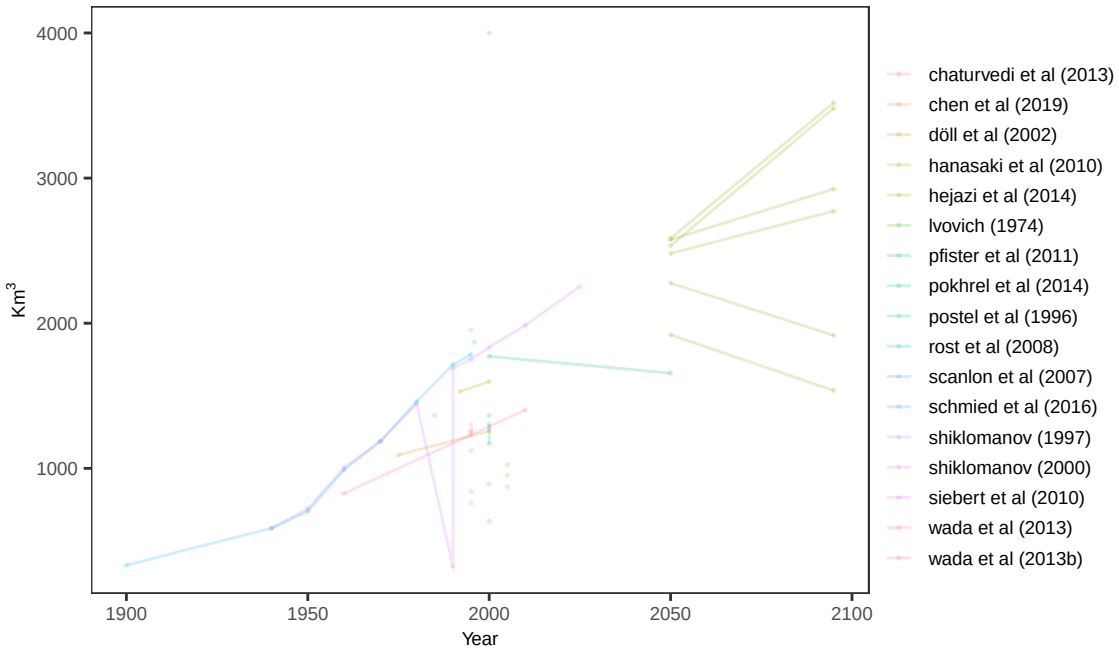



```
# PLOT ALL ESTIMATIONS ###########################################################

def.alpha <- 0.2

plot.iww <- references.full.dt[variable == "iww" & region == "global"] %>%
```

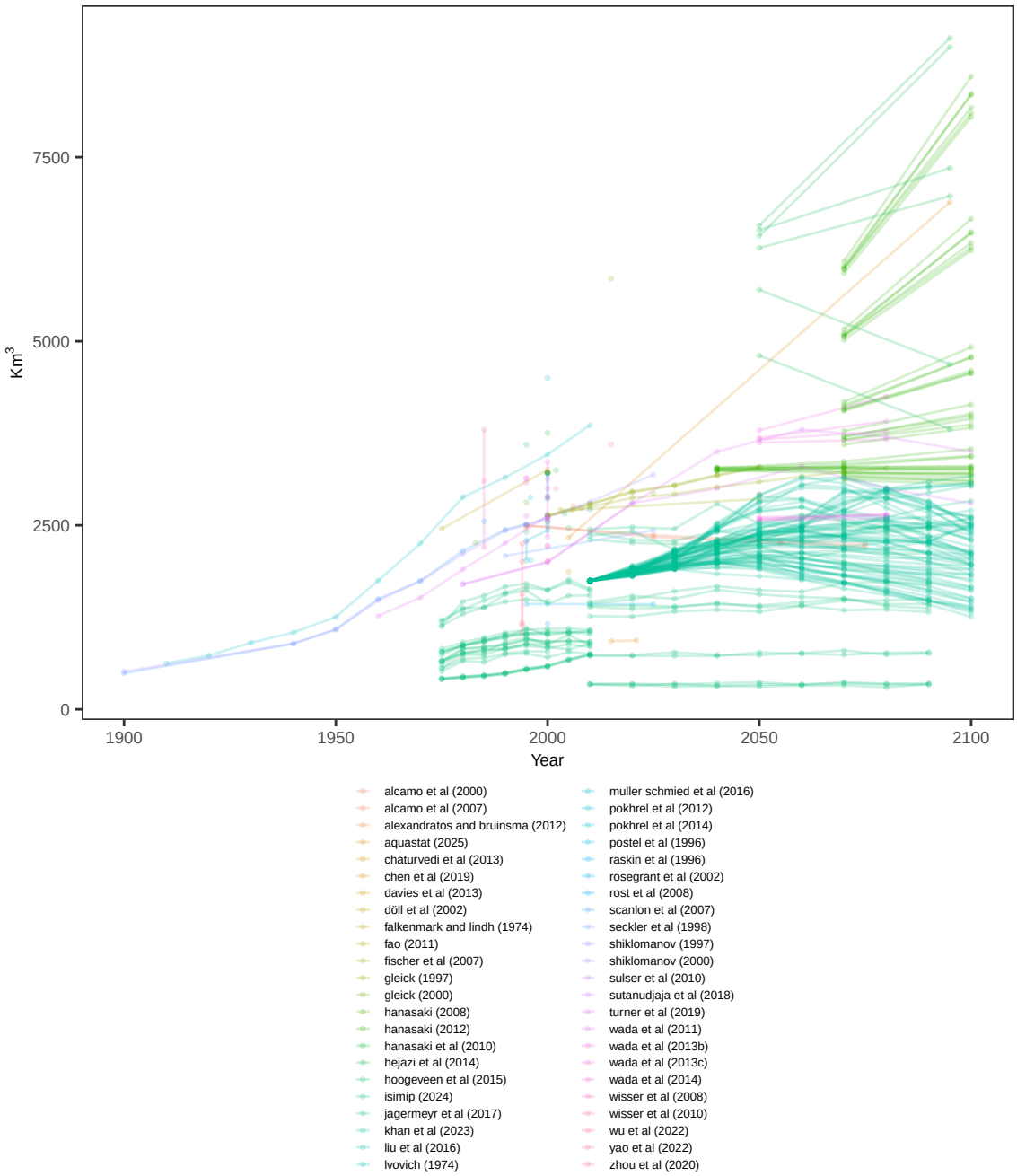
```
  .[, .(author, study, estimation.year, value)] %>%
  na.omit() %>%
  ggplot(., aes(estimation.year, value, color = author, group = study)) +
  geom_point(alpha = def.alpha, size = 0.5) +
  labs(x = "Year", y = bquote("Km"^3)) +
  scale_color_discrete(name = "") +
  geom_line(alpha = def.alpha) +
  theme_AP() +
  guides(color = guide_legend(ncol = 2)) +
  theme(legend.text = element_text(size = 5.5),
        legend.key.width = unit(0.25, "cm"),
          legend.key.height = unit(0.25, "cm"))

plot.iww
```




```
references.full.dt[variable == "iwc" & region == "global"] %>%
  .[, .(author, study, estimation.year, value)] %>%
  na.omit() %>%
  ggplot(., aes(estimation.year, value, color = author, group = study)) +
  geom_point(alpha = def.alpha, size = 0.2) +
  labs(x = "Year", y = bquote("Km"^3)) +
  scale_color_discrete(name = "") +
  geom_line(alpha = def.alpha) +
  theme_AP()
```




```
plot.iww +
  theme(legend.position = "bottom",
        legend.text = element_text(size = 4.8))
```



2.1 The garden of forking paths

```
# DEFINE THE UNCERTAINTY SPACE ######################################################

# Target year ------------------------------------------------------------------

## Defined above

# Target year interval ---------------------------------------------------------
```

```r
target_year_interval <- c("yes", "no")

# Interval publication ----------------------------------------------------

interval <- c(10, 15, 20)

# Metrics of study --------------------------------------------------------

metrics <- c("cv", "range", "sd", "var", "entropy", "iqr")

# Inclusion criteria ------------------------------------------------------

inclusion_criteria <- c("all", "exclude_before_1990")

# Rolling windows ---------------------------------------------------------

rolling_window_factor <- c(1, 0.5)

# Define the forking paths ------------------------------------------------

forking_paths <- expand.grid(target_year = target_year,
                             target_year_interval = target_year_interval,
                             interval = interval,
                             inclusion_criteria = inclusion_criteria,
                             rolling_window_factor = rolling_window_factor,
                             metric = c(metrics, paste(metrics, "_normalized", sep = ""))) %>%
  data.table()

# Number of simulations ---------------------------------------------------

nrow(forking_paths)
```

```
## [1] 1152
```

```r
# RUN MODEL ###################################################################

trend <- list()

for (i in 1:nrow(forking_paths)) {

  trend[[i]] <- forking_paths_fun(dt = references.full.dt,
                                  target_year = forking_paths[[i, "target_year"]],
                                  target_year_interval = forking_paths[[i, "target_year_interva
                                  interval = forking_paths[[i, "interval"]],
                                  rolling_window_factor = forking_paths[[i, "rolling_window_fa
                                  inclusion_criteria = forking_paths[[i, "inclusion_criteria"]]
                                  metric = forking_paths[[i, "metric"]])
}
```

```r
# ARRANGE DATA ##################################################################

output.dt <- lapply(trend, function(x) x[["results"]]) %>%
  do.call(rbind, .) %>%
  data.table() %>%
  setnames(., "V1", "trend")

final.dt <- cbind(forking_paths, output.dt)

# Export simulations ------------------------------------------------------

fwrite(final.dt, "forking.paths.dataset.csv")

# Print the fraction of simulations in each classification ----------------------

final.dt %>%
  .[, .(total = .N), trend] %>%
  .[, fraction:= total / nrow(output.dt)] %>%
  print()
```

```
##           trend total   fraction
##          <char> <int>      <num>
## 1:       Random   490 0.42534722
## 2:    Ascending   306 0.26562500
## 3:   Descending   308 0.26736111
## 4: single point    48 0.04166667
```

```r
# Now remove all simulations that produced just one single point ---------------

final.dt <- final.dt[!trend == "single point"]

# Simulations that did not lead to a reduction in uncertainty ------------------

final.dt %>%
  .[, .(total = .N), trend] %>%
  .[, fraction:= total / nrow(output.dt)] %>%
  .[!trend == "Descending"] %>%
  .[, sum(fraction)]
```

```
## [1] 0.6909722
```

```r
# PLOTS FORKING PATHS EXAMPLES ##################################################

plots.dt <- lapply(trend, function(x) x[["plot"]])

random.plots <- c(1, 986, 345)
decreasing.plots <- c(1093, 556, 4)
increasing.plots <- c(10, 602, 770)
```

```
out.random <- out.decreasing <- out.increasing <- list()

for (i in 1:length(random.plots)) {

  out.random[[i]] <- plot_plots_forking_paths_fun(random.plots[i])
  out.decreasing[[i]] <- plot_plots_forking_paths_fun(decreasing.plots[i])
  out.increasing[[i]] <- plot_plots_forking_paths_fun(increasing.plots[i])
}

pt.random <- plot_grid(out.random[[1]] + geom_smooth() + labs(x = "", y = "+ Uncertainty"),
                       out.random[[2]] + geom_smooth() + labs(x = "", y = ""),
                       out.random[[3]] + geom_smooth() + labs(x = "", y = ""),
                       ncol = 3)
```

```
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
```

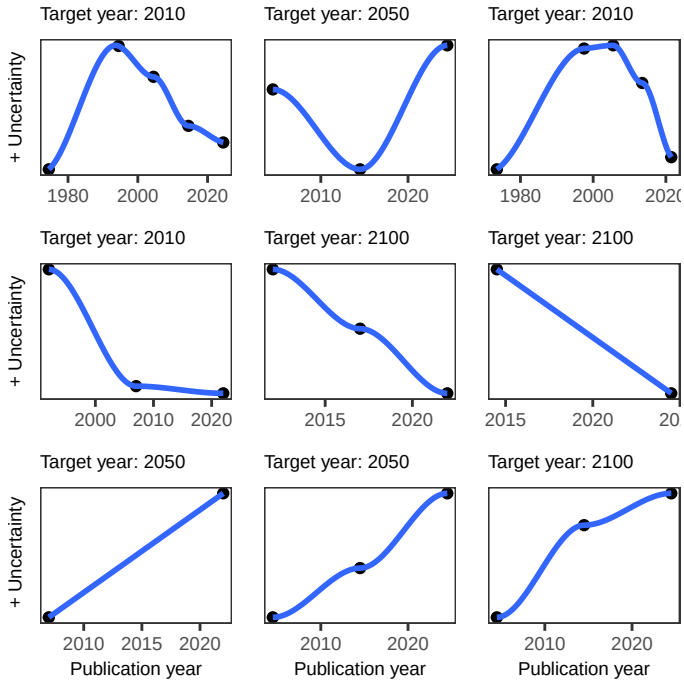
```
pt.decreasing <- plot_grid(out.decreasing[[1]] + geom_smooth() + labs(x = "", y = "+ Uncertaint
                           out.decreasing[[2]] + geom_smooth() + labs(x = "", y = ""),
                           out.decreasing[[3]] + geom_smooth(method = "lm", se = F) + labs(x =
                           ncol = 3)
```

```
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using formula = 'y ~ x'
```

```
pt.increasing <- plot_grid(out.increasing[[1]] + geom_smooth(method = "lm", se = F),
                           out.increasing[[2]] + geom_smooth() + labs(x = "Publication year", y
                           out.increasing[[3]] + geom_smooth() + labs(x = "Publication year", y
                           ncol = 3)
```

```
## `geom_smooth()` using formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
```

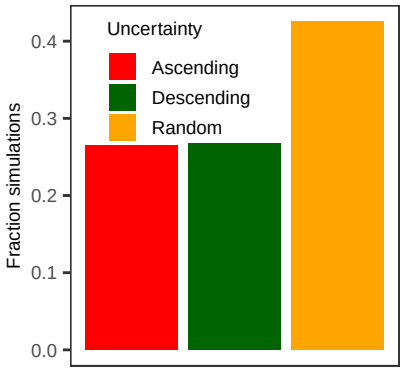
```
plot.examples.trends <- plot_grid(pt.random, pt.decreasing, pt.increasing, ncol = 1)
plot.examples.trends
```




```
# PLOT RESULTS ###################################################################

selected_colors <- c("Ascending" = "red", "Descending" = "darkgreen", "Random" = "orange")

plot.fraction <- final.dt[, .(total = .N), trend] %>%
  .[, fraction:= total / nrow(output.dt)] %>%
  ggplot(., aes(trend, fraction, fill = trend)) +
  geom_bar(stat = "identity") +
  labs(x = "", y = "Fraction simulations") +
  scale_fill_manual(values = selected_colors, name = "Uncertainty") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(axis.ticks.x = element_blank(),
        axis.text.x = element_blank(),
        legend.position = c(0.33, 0.79))
```

```
## Warning: A numeric `legend.position` argument in `theme()` was deprecated in ggplot2
## 3.5.0.
## i Please use the `legend.position.inside` argument of `theme()` instead.
## This warning is displayed once every 8 hours.
## Call `lifecycle::last_lifecycle_warnings()` to see where this warning was
## generated.
```

```
plot.fraction
```

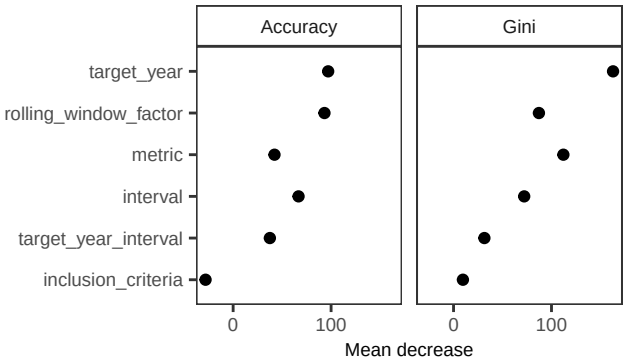



```
# RANDOM FOREST ##################################################################

# Convert categorical variables to factors -----------------------------------

df <- data.frame(final.dt)
df$inclusion_criteria <- as.factor(final.dt$inclusion_criteria)
df$metric <- as.factor(final.dt$metric)
df$trend <- as.factor(df$trend)
df$target_year_interval <- as.factor(df$target_year_interval)

# Train the model ------------------------------------------------------------

rf_model <- randomForest(trend ~ target_year + target_year_interval + interval +
                           inclusion_criteria + rolling_window_factor + metric,
                         data = df, importance = TRUE)

# View variable importance ---------------------------------------------------

dt_rf_model <- data.frame(importance(rf_model))
dt_rf_model
```

```
##                         Ascending Descending    Random MeanDecreaseAccuracy
## target_year              53.50264   80.53395  81.71733              97.03107
## target_year_interval     31.04340   21.79852  18.59561              37.51582
## interval                 38.45521   39.12145  55.38863              66.76510
## inclusion_criteria      -25.51671  -12.57365 -12.79991             -28.15031
## rolling_window_factor    53.31723   44.54171  90.84175              93.23765
## metric                   42.34925   22.68413  22.06579              42.22436
##                         MeanDecreaseGini
## target_year                   162.843039
## target_year_interval           31.501762
## interval                       72.147306
## inclusion_criteria              9.578704
## rolling_window_factor          87.155278
## metric                        112.122009
```

```
# Plot -----------------------------------------------------------------------
```

```
plot.rf <- dt_rf_model %>%
  rownames_to_column(., var = "factors") %>%
  data.table() %>%
  setnames(., c("MeanDecreaseAccuracy", "MeanDecreaseGini"),
           c("Accuracy", "Gini")) %>%
  melt(., measure.vars = c("Accuracy", "Gini")) %>%
  ggplot(., aes(reorder(factors, value), value)) +
  geom_point() +
  coord_flip() +
  facet_wrap(~variable) +
  scale_y_continuous(breaks = breaks_pretty(n = 3)) +
  labs(x = "", y = "Mean decrease") +
  theme_AP()

plot.rf
```

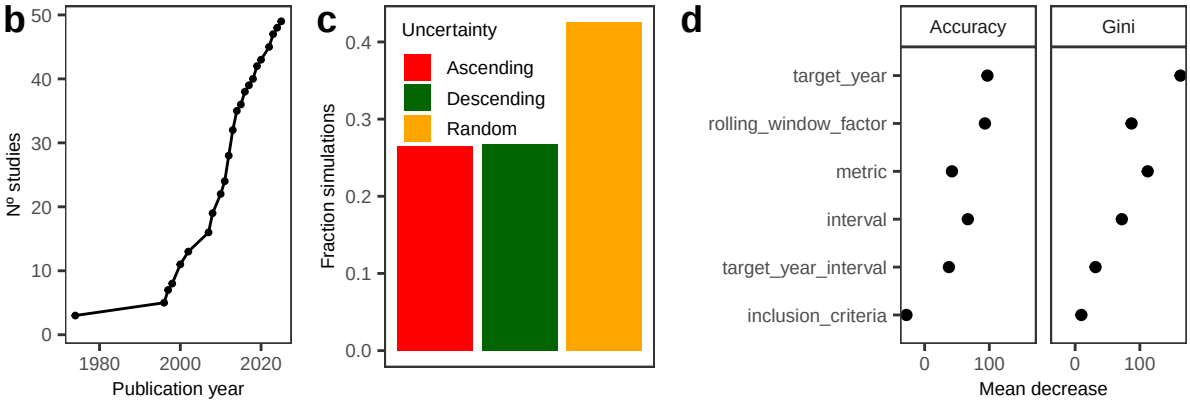



```
bottom <- plot_grid(cumulative.iww, plot.fraction, plot.rf, ncol = 3, labels = c("b", "c", "d"),
          rel_widths = c(0.26, 0.3, 0.44))
```

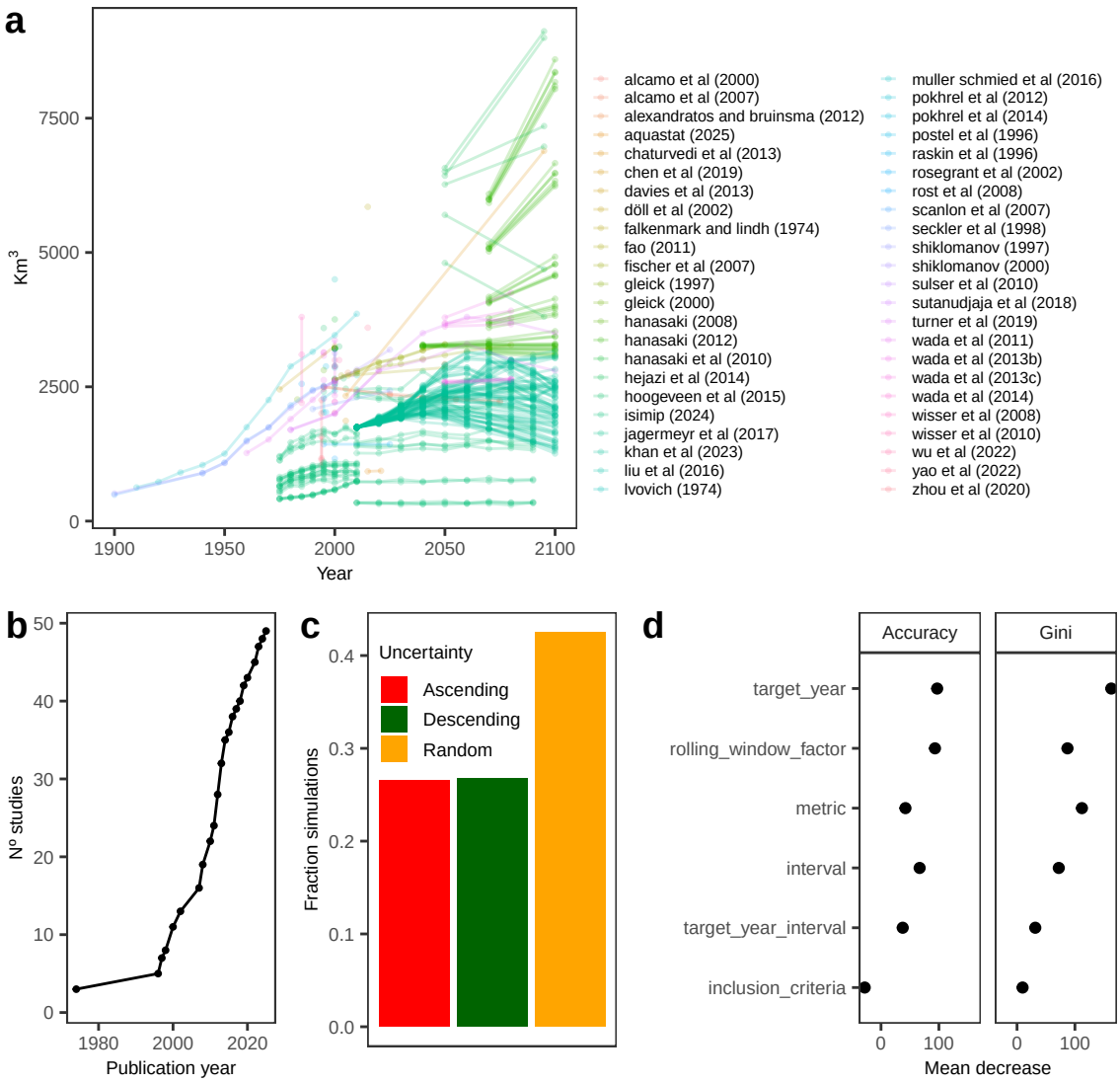
```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_line()`).
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_point()`).
```

```
bottom
```

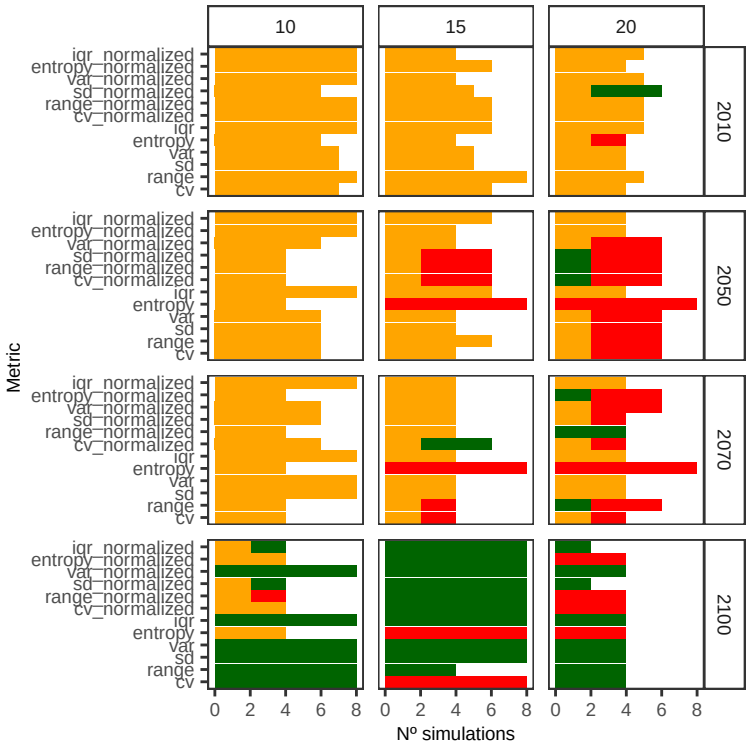


```
#
final.faceted.plot <- plot_grid(plot.iww, bottom, ncol = 1, labels = c("a", ""),
                                rel_heights = c(0.55, 0.45))

final.faceted.plot
```




```
# RESULTS FACETED BY INTERVAL AND TARGET YEAR, X AXIS METRICS ###################

plot.faceted.metrics <- final.dt %>%
  ggplot(., aes(x = factor(metric), fill = trend)) +
  geom_bar(position ="identity") +
  facet_grid(target_year ~ interval, scales = "free_y") +
  scale_fill_manual(values = selected_colors, name = "Uncertainty") +
  theme_AP() +
  labs(x = "Metric", y = "Nº simulations") +
  theme(legend.position = "none") +
  coord_flip()
```

```
plot.faceted.metrics
```

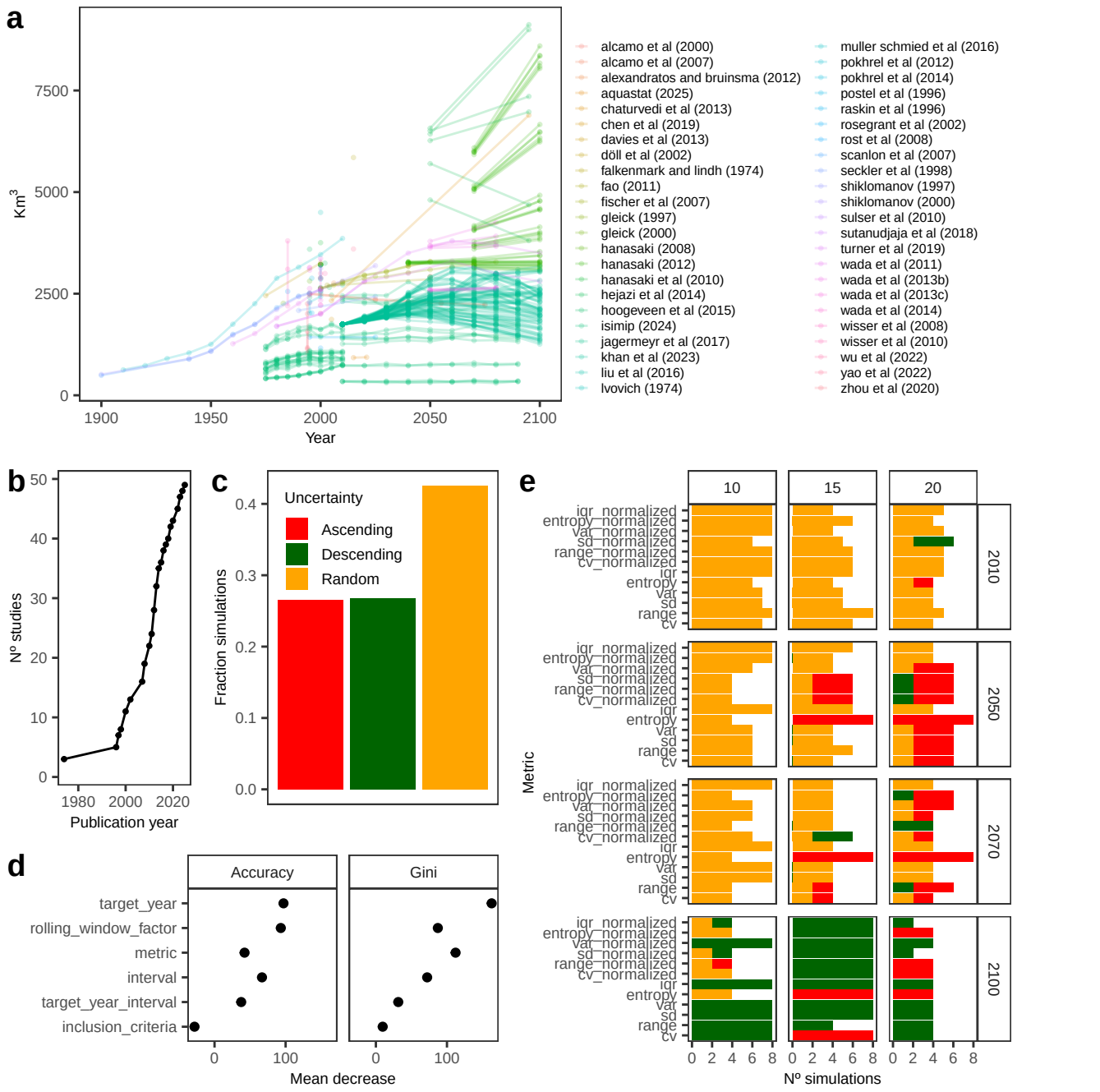



```
bottom <- plot_grid(cumulative.iww, plot.fraction, ncol = 2, rel_widths = c(0.4, 0.6),
                    labels = c("b", "c"))
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_line()`).
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_point()`).
```

```
left <- plot_grid(bottom, plot.rf, ncol = 1, labels = c("", "d"), rel_heights = c(0.6, 0.4))
bottom2 <- plot_grid(left, plot.faceted.metrics, ncol = 2, labels = c("", "e"))
plot_grid(plot.iww, bottom2, rel_heights = c(0.42, 0.58), ncol = 1, labels = c("a", ""))
```

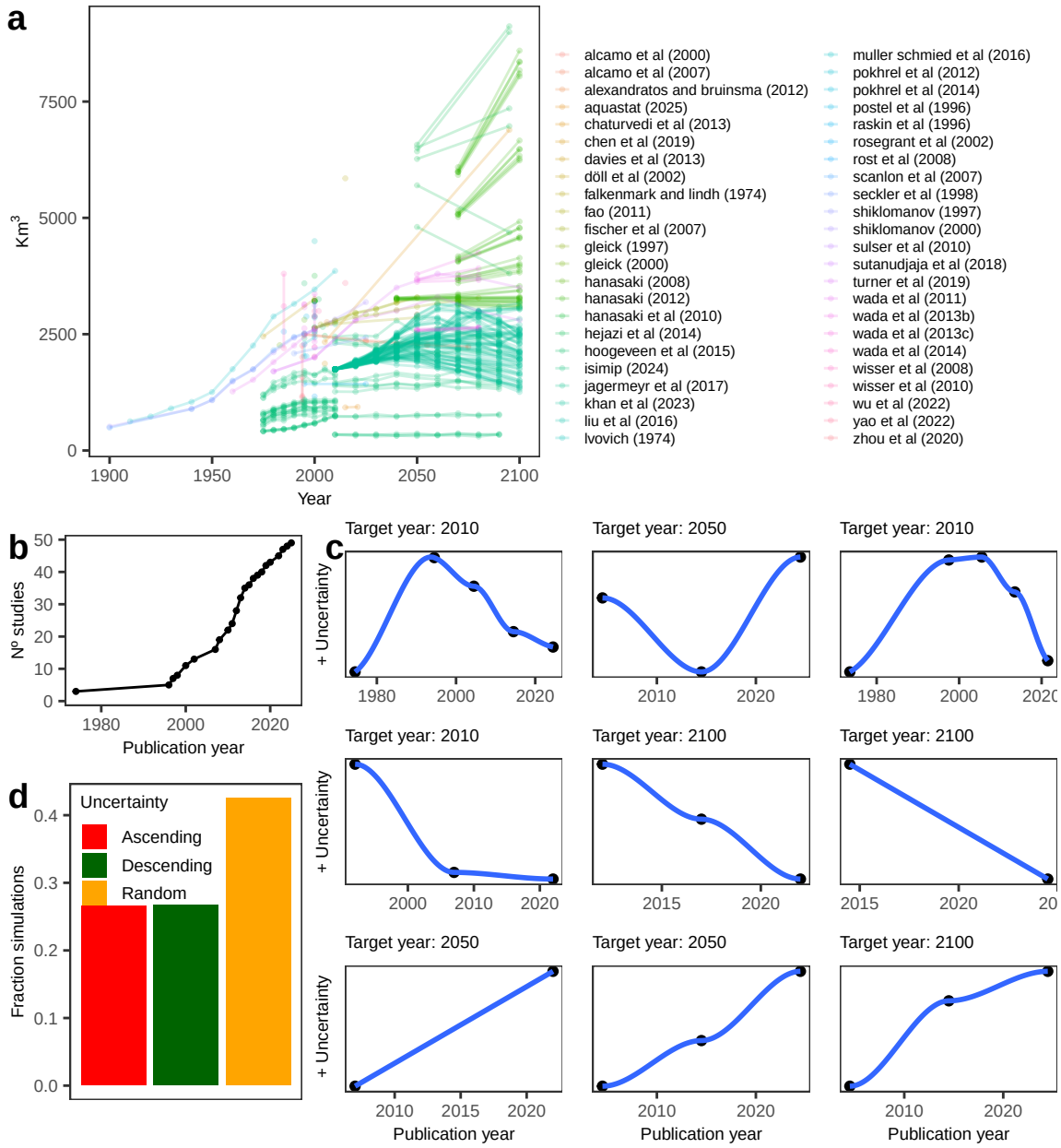



```
left <- plot_grid(cumulative.iww, plot.fraction, ncol = 1, rel_heights = c(0.4, 0.6),
                  labels = c("b", "d"))
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_line()`).
```

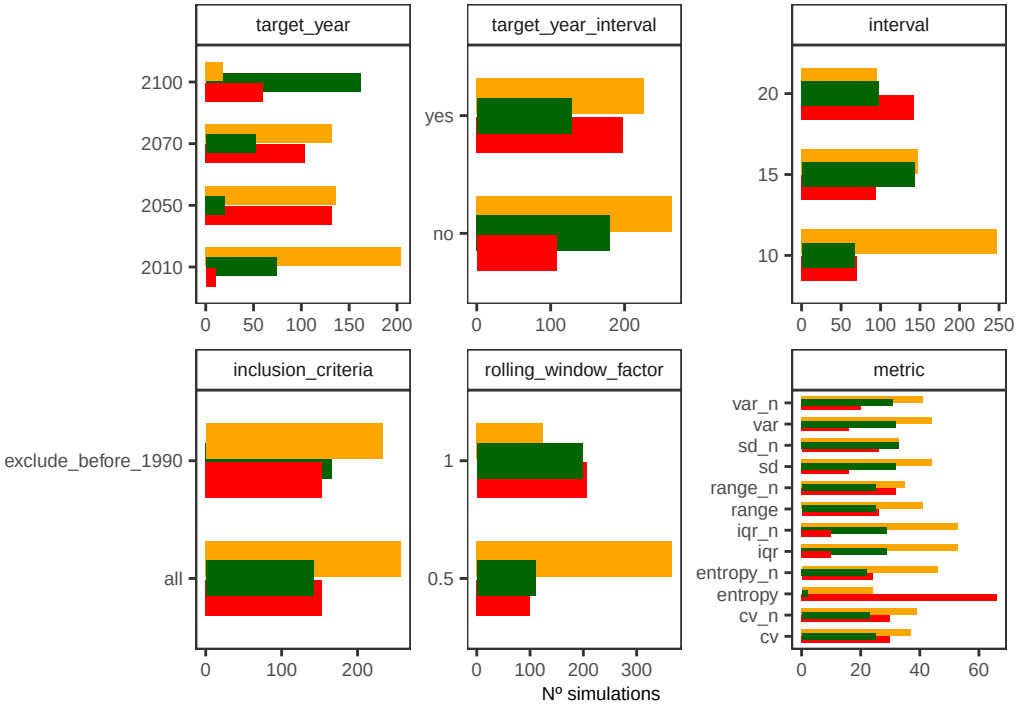
```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_point()`).
```

```
bottom <- plot_grid(left, plot.examples.trends, ncol = 2, rel_widths = c(0.3, 0.7),
                    labels = c("", "c"))
plot_grid(plot.iww, bottom, ncol = 1, rel_heights = c(0.46, 0.54), labels = c("a", ""))
```




```
final.dt %>%
  melt(., measure.vars = c("target_year", "target_year_interval", "interval",
                           "inclusion_criteria", "rolling_window_factor", "metric")) %>%
  .[, .N, .(variable, value, trend)] %>%
  .[ , value := gsub("_normalized", "_n", value)] %>%
  ggplot(., aes(value, N, fill = trend)) +
  scale_fill_manual(values = selected_colors, name = "Uncertainty") +
  geom_bar(stat = "identity", position = position_dodge(0.5)) +
  facet_wrap(~variable, scale = "free") +
  labs(x = "", y = "Nº simulations") +
  theme_AP() +
  coord_flip() +
  theme(legend.position = "none")
```

```
## Warning in melt.data.table(., measure.vars = c("target_year",
## "target_year_interval", : 'measure.vars' [target_year, target_year_interval,
## interval, inclusion_criteria, ...] are not all of the same type. By order of
## hierarchy, the molten data value column will be of type 'character'. All
## measure variables not of type 'character' will be coerced too. Check DETAILS in
## ?melt.data.table for more on coercion.
```



3 Session information

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

sessionInfo()
```

```
## R version 4.3.3 (2024-02-29)
## Platform: aarch64-apple-darwin20 (64-bit)
## Running under: macOS Sonoma 14.2.1
##
## Matrix products: default
## BLAS:   /Library/Frameworks/R.framework/Versions/4.3-arm64/Resources/lib/libRblas.0.dylib
## LAPACK: /Library/Frameworks/R.framework/Versions/4.3-arm64/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
##
## time zone: Europe/London
## tzcode source: internal
##
## attached base packages:
## [1] parallel  stats     graphics  grDevices utils     datasets  methods
## [8] base
##
## other attached packages:
##  [1] randomForest_4.7-1.2 brms_2.22.0          Rcpp_1.0.13-1
##  [4] mgcv_1.9-1           nlme_3.1-166         microbenchmark_1.5.0
##  [7] lme4_1.1-35.5        Matrix_1.6-5         here_1.0.1
## [10] doParallel_1.0.17    iterators_1.0.14     foreach_1.5.2
## [13] rworldmap_1.3-8      sp_2.1-4             countrycode_1.6.0
## [16] ncdf4_1.23           scales_1.3.0         wesanderson_0.3.7
## [19] benchmarkme_1.0.8    cowplot_1.1.3        lubridate_1.9.3
## [22] forcats_1.0.0        stringr_1.5.1        dplyr_1.1.4
## [25] purrr_1.0.2          readr_2.1.5          tidyr_1.3.1
## [28] tibble_3.2.1         ggplot2_3.5.1        tidyverse_2.0.0
## [31] data.table_1.16.2    openxlsx_4.2.7.1
##
## loaded via a namespace (and not attached):
##  [1] Rdpack_2.6.2          rlang_1.1.4           magrittr_2.0.3
##  [4] matrixStats_1.4.1     compiler_4.3.3        loo_2.8.0
##  [7] vctrs_0.6.5           maps_3.4.2.1          crayon_1.5.3
## [10] pkgconfig_2.0.3       fastmap_1.2.0         backports_1.5.0
## [13] labeling_0.4.3        utf8_1.2.4            rmarkdown_2.29
## [16] tzdb_0.4.0            nloptr_2.1.1          tinytex_0.54
## [19] xfun_0.49             terra_1.7-78          R6_2.5.1
## [22] stringi_1.8.4         boot_1.3-31           estimability_1.5.1
## [25] knitr_1.49            fields_16.3           bayesplot_1.11.1
## [28] splines_4.3.3         timechange_0.3.0      tidyselect_1.2.1
```

```
## [31] rstudioapi_0.17.1     abind_1.4-8           yaml_2.3.10
## [34] codetools_0.2-20      lattice_0.22-6        withr_3.0.2
## [37] bridgesampling_1.1-2  benchmarkmeData_1.0.4 posterior_1.6.0
## [40] coda_0.19-4.1         evaluate_1.0.1        RcppParallel_5.1.9
## [43] zip_2.3.1             pillar_1.9.0          tensorA_0.36.2.1
## [46] checkmate_2.3.2       distributional_0.5.0  generics_0.1.3
## [49] rprojroot_2.0.4       hms_1.1.3             rstantools_2.4.0
## [52] munsell_0.5.1         minqa_1.2.8           sensobol_1.1.5
## [55] xtable_1.8-4          glue_1.8.0            emmeans_1.10.5
## [58] tools_4.3.3           mvtnorm_1.3-2         dotCall64_1.2
## [61] grid_4.3.3            rbibutils_2.3         colorspace_2.1-1
## [64] raster_3.6-30         cli_3.6.3             spam_2.11-0
## [67] fansi_1.0.6           viridisLite_0.4.2     Brobdingnag_1.2-9
## [70] gtable_0.3.6          digest_0.6.37         farver_2.1.2
## [73] htmltools_0.5.8.1     lifecycle_1.0.4       httr_1.4.7
## [76] MASS_7.3-60.0.1
```

```
## Return the machine CPU ----------------------------------------------------

cat("Machine:     "); print(get_cpu()$model_name)
```

```
## Machine:
## [1] "Apple M1 Max"
```

```
## Return number of true cores -----------------------------------------------

cat("Num cores:   "); print(detectCores(logical = FALSE))
```

```
## Num cores:
## [1] 10
```

```
## Return number of threads --------------------------------------------------

cat("Num threads: "); print(detectCores(logical = FALSE))
```

```
## Num threads:
## [1] 10
```