```
# Growth models for even-aged stands of Hesperocyparis macrocarpa and H. lusitanica with Site Index & 300 Index estimation
#
# The growth models are described in: Kimberley M.O. and Watt, M.S. Growth models for even-aged stands of Hesperocyparis macrocarpa and
#   Hesperocyparis lusitanica.
#
# R-code was written by Mark Kimberley in December 2022.
#
# The models are implemented in the following two functions:
# 1. Yield_table - this function produces am annual yield table for a specified 300 Index, Site Index, and stocking history.
#   Note that 300 Index is defined as the stem volume MAI at age 30 years for a stand growing at 300 stems/ha, and Site Index
#   is defined as the Mean Top Height at age 30 years
# 2. Calibrated_yield_table - this function estimates Site Index and 300 Index from a plot measurement and stand density
#   and thinning history details. It also produces an annual yield table for the plot.
#
# Code for both functions is below along with code for other internally referenced functions.
#

# Parameters of stand-level volume function

uv <- 0.294
vv <- 0.397
wv <- 0.587

# MTH_mod - Function for predicting Mean Top Height (MTH, m). Parameters are: Species ("MAC"or "LUS"), Age (years), and Site Index (SI, m)

MTH_mod <- function(Species = "MAC", Age, SI) {
```

```
  if (Species=="MAC") {
    ah <- 47.37
    ch <- 1.062
  }
  if (Species=="LUS") {
    ah <- 38.79
    ch <- 1.099
  }
  0.3 + (ah - 0.3) * (1 - (1 - ((SI - 0.3)/(ah - 0.3))^(1/ch))^(Age/30))^ch
}

# TBH_mod - Function for predicting age when MTH equals 1.4 m breast height age (years). Parameters are: Species ("MAC"or "LUS") and
#   Site Index (SI, m)

TBH_mod <- function(Species = "MAC", SI) {
  if (Species=="MAC") {
    ah <- 47.37
    ch <- 1.062
  }
  if (Species=="LUS") {
    ah <- 38.79
    ch <- 1.099
  }
  30*log(1 - (1.1/(ah - 0.3))^(1/ch))/log(1 - ((SI - 0.3)/(ah - 0.3))^(1/ch))
}
```

```
# DBH_mod - Function for predicting Diameter at 1.4 m breast height (DBH, cm). Parameters are: Species ("MAC"or "LUS"), Age (years),
#   D_30 (DBH at age 30 years and 300 stems/ha, cm), Site Index (SI, m), and stand density (N, stems/ha)

DBH_mod <- function(Species="MAC", Age, D_30, SI, N) {
  if (Species=="MAC") {
    ad <- 83.14
    cd <- 0.7100
    dd <- 0.4213
    fd <- 0.2645
    g1d <- 20.68
    g2d <- -0.62
  }
  if (Species=="LUS") {
    ad <- 83.28
    cd <- 0.6974
    dd <- 0.3659
    fd <- 0.4624
    g1d <- 32.02
    g2d <- -2.39
  }
  TBH <- TBH_mod(Species, SI)
  D300 <- ad*(D_30/ad)^(((Age - TBH)/(30 - TBH))^(-cd))
  DBH_mod <- D300 - (dd/fd)*(log(N) - log(300))*log(1 + exp(fd*(D300 - (g1d + g2d*log(N)))))
  if ((Age<TBH)|(DBH_mod<0)) {DBH_mod <- 0}
  DBH_mod
}
```

```
# Vol_mod - Function for predicting stem volume (m3/ha). Parameters are: Mean Top Height (MTH, m), and Basal Area (BA, m2/ha)

Vol_mod <- function(MTH, BA) {
  Vol_mod <- MTH*BA*(vv*(MTH - 1.4)^(-wv)+uv)
  if (BA == 0|MTH == 0) {Vol_mod <- 0}
  Vol_mod
}

# Calc_BA - Function for calculating Basal Area (BA, m2/ha). Parameters are: Stand Density (N, stems/ha) and Breast Height Diameter (DBH, cm)

Calc_BA <- function(N, DBH) {
  N*pi*(DBH/200)^2
}

# Calc_I300 - Function for calculating 300 Index (m3/ha/yr, defined as the stem volume MAI at age 30 years for a stand growing at 300 stems/ha).
#   Parameters are: Site Index (SI, m) and D_30 (DBH at age 30 years and 300 stems/ha, cm)

Calc_I300 <- function(D_30, SI) {
  (300*pi*SI*D_30^2)*(vv*(SI - 1.4)^(-wv) + uv)/(40000*30)
}

# Calc_D30 - Function for calculating D_30 (DBH at age 30 years and 300 stems/ha, cm). Paramters are: 300 Index (I300, m3/ha/yr) and Site Index
(SI, m)

Calc_D30 <- function(I300, SI) {
  200*sqrt(30*I300/(SI*300*pi*(vv*(SI - 1.4)^(-wv) + uv)))
```

```
}

# Thin_age_shift - Function for estimating thinning age shift (Thin_age_shift, years) using the bisection method. Parameters are: Species
#   ("MAC" or "LUS"), Age (T, years), Stand Density before thinning (N1, stems/ha), Stand Density after thinning (N2, stems/ha), Thinning
#   coefficient (k, where BA2/BA1 = (N2/N1)^k), and Site Index (SI, m)

Thin_age_shift <- function(Species = "MAC", T, N1, N2, k, D_30, SI) {
  TBH <- TBH_mod(Species, SI)
  DBH_pre_thin <- DBH_mod(Species, T, D_30, SI, N1)
  DBH_post_thin <- DBH_pre_thin*((N1/N2)^((1 - k)/2))
  Agelo <- TBH + 1
  Ageup <- T - TBH + 20
  for (j in 1:20) {
    Agemid <- (Agelo + Ageup) / 2
    flo <- DBH_mod(Species,Agelo, D_30, SI, N2) - DBH_post_thin
    fup <- DBH_mod(Species,Ageup, D_30, SI, N2) - DBH_post_thin
    fmid <- DBH_mod(Species,Agemid, D_30, SI, N2) - DBH_post_thin
    if (flo*fmid < 0) {Ageup <- Agemid}
    if (flo*fmid >= 0) {Agelo <- Agemid}
  }
  Agemid - T
}

# Yield_table - Function for producing a cypress yield table for a specified 300 Index, Site Index, and stocking history.
# Parameters are: Species ("MAC" or "LUS"), Max age of yield table (Max_age, years), 300 Index (I300, m3/ha/yr, defined as the stem
#   volume MAI at age 30 years for a stand growing at 300 stems/ha), Site Index (SI, m, defined as MTH at age 30 years),
```

```
#   Stand density at planting (Initial_N, stems/ha), Number of thinnings (N_thins, 0 or more), Thin_age (vector of length N_thins
#   containing ages (years, must be whole numbers) of each thinning), Thin_N (vector of length N_thins containing stand density after
#   each thinning (stems/ha)), Thin_k (vector of length N_thins containing coefficients k of each thinning, where BA2/BA1 = (N2/N1)^k)
# The function produces a list containing the following items:
#   Species, I300 (300 Index), SI (Site Index), Yield_table, Thinning_detail
#   Yield_table is a dataframe containing annual predictions of the following variables:
#     YT_Age - age in years
#     YT_Adj_Age - age in years adjusted for thinning age shifts)
#     YT_Thin_Age_shift - age shift in years at each thinning
#     YT_N - stand density in stems/ha
#     YT_DBH - Breast height diameter in cm
#     YT_MTH - Mean top height in m
#     YT_BA - Basal area in m2/ha
#     YT_Vol - Stem volume in m3/ha
#   Thinning_detail is a dataframe containing details of ach thinning as follows:
#     TD_Age - age of thinning in years
#     TD_k  - thinning coefficient
#     TD_MTH  - Mean top height at time of thinning in m
#     TD_N_pre_thin - Stand density before thinning in stems/ha
#     TD_N_post_thin - Stand density after thinning in stems/ha
#     TD_DBH_pre_thin - Diameter at breast height before thinning in cm
#     TD_DBH_post_thin - Diameter at breast height after thinning in cm
#     TD_BA_pre_thin - Basal area before thinning in m2/ha
#     TD_BA_post_thin - Basal area after thinning in m2/ha
#     TD_Vol_pre_thin - Stem volume before thinning in m3/ha
#     TD_Vol_post_thin - Stem volume after thinning in m3/ha
```

```
Yield_table <- function(Species, Max_age, I300, SI, Initial_N, N_thins = 0, Thin_age, Thin_N, Thin_k) {
  # Parameters of mortality function
  if (Species=="MAC") {
    km <- 0.00
    mm <- 0.0314
    nm <- 1.41
  }
  if (Species=="LUS") {
    km <- 0.0049
    mm <- 0.0314
    nm <- 1.41
  }

  # Cypress mortality model parameters
    km <- 0.0035
    mm <- 0.0314
    nm <- 1.41

  # Declare yield table vectors
  YT_Age <- c(0:Max_age)
  YT_Adj_Age <- c(0:Max_age)
  YT_Thin_Age_shift <- rep(0, Max_age+1)
  YT_N <- rep(NA, Max_age+1)
  YT_DBH <- rep(NA, Max_age+1)
  YT_MTH <- rep(NA, Max_age+1)
```

```
YT_BA <- rep(NA, Max_age+1)

YT_Vol <- rep(NA, Max_age+1)


# Use default thinning coefficient of 0.7 if not specified

if (missing(Thin_k)) {Thin_k <- rep(0.7,N_thins)}


# Declare thinning detail vectors

TD_Age <- rep(NA, N_thins)

TD_k <- rep(NA, N_thins)

TD_MTH <- rep(NA, N_thins)

TD_N_pre_thin <- rep(NA, N_thins)

TD_N_post_thin <- rep(NA, N_thins)

TD_DBH_pre_thin <- rep(NA, N_thins)

TD_DBH_post_thin <- rep(NA, N_thins)

TD_BA_pre_thin <- rep(NA, N_thins)

TD_BA_post_thin <- rep(NA, N_thins)

TD_Vol_pre_thin <- rep(NA, N_thins)

TD_Vol_post_thin <- rep(NA, N_thins)


# Stand metrics at age zero

YT_N[1] <- Initial_N

YT_MTH[1] <- 0.3

YT_DBH[1] <- 0

YT_BA[1] <- 0

YT_Vol[1] <- 0
```

```
# Age when MTH reaches breast height (1.4 m)
TBH <- TBH_mod(Species, SI)

# Quadratic mean DBH for stand density 300 stems/ha at age 30 years
D_30 <- Calc_D30(I300, SI)

# Generate annual yield table from age 1 to Max_age
for (i in 1:Max_age) {

  # adjusted age
  YT_Adj_Age[i + 1] <- YT_Adj_Age[i] + 1

  # MTH
  YT_MTH[i + 1] <- MTH_mod(Species, YT_Age[i + 1], SI)

  # Reinekes SDI divided by 1000
  SDI <- (0.405*YT_N[i]*(0.394*YT_DBH[i]/10)^1.605)/1000

  # Annual % mortality
  Mort <- 100*(km+mm*SDI^nm)

  # Stand density
  YT_N[i + 1] <- YT_N[i]*(1 - Mort/100)

  # DBH
  YT_DBH[i + 1] <- DBH_mod(Species, YT_Adj_Age[i + 1], D_30, SI, YT_N[i + 1])
```

```
# Basal area
YT_BA[i + 1] <- Calc_BA(YT_N[i + 1], YT_DBH[i + 1])

# Volume
YT_Vol[i + 1] <- Vol_mod(YT_MTH[i + 1], YT_BA[i + 1])

# Test for thinning
Thin <- FALSE
if (N_thins != 0) {
  for (thin in 1:N_thins) {
    if(YT_Age[i + 1] == Thin_age[thin]) {
      Thin <- TRUE
      Thin_number <- thin
      N_post_thin <- Thin_N[thin]
      k <- Thin_k[thin]
    }
  }

  if (Thin == TRUE) {
    # DBH before thinning
    DBH_pre_thin <- YT_DBH[i + 1]

    # Stand density before thinning
    N_pre_thin <- YT_N[i + 1]
```

```
# DBH after thinning obtained using thinning coefficient k
DBH_post_thin <- DBH_pre_thin*((N_pre_thin/N_post_thin)^((1-k)/2))

# Update stand density yield table matrix to reflect thinning
YT_N[i + 1] <- N_post_thin

# Update DBH yield table matrix to reflect thinning
YT_DBH[i + 1] <- DBH_post_thin

# Basal area
YT_BA[i + 1] <- Calc_BA(YT_N[i + 1], YT_DBH[i + 1])

# Volume
YT_Vol[i + 1] <- Vol_mod(YT_MTH[i + 1], YT_BA[i + 1])

# Determine thinning age-shift
Age_shift <- Thin_age_shift(Species,YT_Adj_Age[i + 1], N_pre_thin, N_post_thin, k, D_30, SI)
YT_Thin_Age_shift[i + 1] <- YT_Thin_Age_shift[i + 1] + Age_shift

# Determine additional thinning age-shift to be applied to year following thinning
#   (equals 50% initial age shift to a maximum of 0.25 years)
YT_Thin_Age_shift[i + 2] <- pmax(pmin(Age_shift*0.5, 0), -0.25)

# Record details of thinning
TD_Age[Thin_number] <- Thin_age[Thin_number]
TD_k[Thin_number] <- k
```

```
      TD_N_pre_thin[Thin_number] <- N_pre_thin
      TD_N_post_thin[Thin_number] <- N_post_thin
      TD_MTH[Thin_number] <- YT_MTH[i + 1]
      TD_DBH_pre_thin[Thin_number] <- DBH_pre_thin
      TD_DBH_post_thin[Thin_number] <- DBH_post_thin
      TD_BA_pre_thin[Thin_number] <- Calc_BA(N_pre_thin, DBH_pre_thin)
      TD_BA_post_thin[Thin_number] <- Calc_BA(N_post_thin, DBH_post_thin)
      TD_Vol_pre_thin[Thin_number] <- Vol_mod(YT_MTH[i + 1], TD_BA_pre_thin[Thin_number])
      TD_Vol_post_thin[Thin_number] <- Vol_mod(YT_MTH[i + 1], TD_BA_post_thin[Thin_number])
    }
    # Update adjusted age by adding age shift
    YT_Adj_Age[i + 1] <- YT_Adj_Age[i + 1] + YT_Thin_Age_shift[i + 1]
  }
}

# Save yield table vectors in dataframe
Yield_table <- data.frame(YT_Age, YT_Adj_Age, YT_Thin_Age_shift, YT_N, YT_DBH, YT_MTH, YT_BA, YT_Vol)

# Save thinning details in dataframe
Thinning_detail <- data.frame(TD_Age, TD_k, TD_N_pre_thin, TD_N_post_thin, TD_MTH, TD_DBH_pre_thin, TD_DBH_post_thin,
  TD_BA_pre_thin, TD_BA_post_thin, TD_Vol_pre_thin, TD_Vol_post_thin)
Thinning_detail <- Thinning_detail[order(Thinning_detail$TD_Age),]

# Save all outputs in list
Yield_table <- list(Species, I300, SI, Yield_table, Thinning_detail)
names(Yield_table) <- c("Species", "300 Index", "Site Index", "Yield table", "Thinning details")
```

```
  return(Yield_table)
}

# Yield table examples:

# C. macrocarpa stand planted at 1000 stems/ha and unthinned
Yield_table(Species="MAC", Max_age=60, I300=25, SI=25, Initial_N=1000, N_thins=0)

# C. lusitanica stand planted at 1000 stems/ha and thinned to 700 stems/ha at age 10 years using thinning coefficient of 0.8
Yield_table(Species="LUS", Max_age=60, I300=25, SI=25, Initial_N=1000, N_thins=1, Thin_age=10, Thin_N=700, Thin_k=0.8)

# C. macrocarpa stand planted at 1000 stems/ha and thinned at ages 10, 20 and 25 years to 700, 500 and 300 stems/ha using default
#   thinning coefficient
Yield_table(Species="MAC", Max_age=60, I300=20, SI=30, Initial_N=1000, N_thins=3, Thin_age=c(10,20,25), Thin_N=c(700,500,300))


# Calibrated_yield_table - Function for estimating cypress Site Index and 300 Index from a plot measurement and stand density and thinning
#   history details. The function also produces an annual yield table.
# Parameters are: Species ("MAC" or "LUS"), Age of measurement (years), Stand density of measurement (N, stems/ha), Mean top height of
#   measurement (MTH, m), Basal area of measurement (BA, m2/h), Max age of yield table (Max_age, years), Stand density at planting
#   (Initial_N, stems/ha), Number of thinnings (N_thins, 0 or more), Thin_age (vector of length N_thins containing ages (years, must be
#   whole numbers) of each thinning), Thin_N (vector of length N_thins containing stand density after each thinning (stems/ha)),
#   Thin_k (vector of length N_thins containing coefficients k of each thinning, where BA2/BA1 = (N2/N1)^k)
# The function produces a list containing the following items:
#   Species, I300 (300 Index, m3/ha/yr), SI (Site Index, m), Yield_table, Thinning_detail
```

```
#   Yield_table is a dataframe containing annual predictions of the following variables:
#     YT_Age - age in years
#     YT_Adj_Age - age in years adjusted for thinning age shifts)
#     YT_Thin_Age_shift - age shift in years at each thinning
#     YT_N - stand density in stems/ha
#     YT_DBH - Breast height diameter in cm
#     YT_MTH - Mean top height in m
#     YT_BA - Basal area in m2/ha
#     YT_Vol - Stem volume in m3/ha
#   Thinning_detail is a dataframe containing details of ach thinning as follows:
#     TD_Age - age of thinning in years
#     TD_k  - thinning coefficient
#     TD_MTH  - Mean top height at time of thinning in m
#     TD_N_pre_thin - Stand density before thinning in stems/ha
#     TD_N_post_thin - Stand density after thinning in stems/ha
#     TD_DBH_pre_thin - Diameter at breast height before thinning in cm
#     TD_DBH_post_thin - Diameter at breast height after thinning in cm
#     TD_BA_pre_thin - Basal area before thinning in m2/ha
#     TD_BA_post_thin - Basal area after thinning in m2/ha
#     TD_Vol_pre_thin - Stem volume before thinning in m3/ha
#     TD_Vol_post_thin - Stem volume after thinning in m3/ha

Calibrated_yield_table <- function(Species, Age, N, MTH, BA, Max_age, Initial_N, N_thins, Thin_age, Thin_N, Thin_k) {
  # Index of calibration age
  meas_index <- as.integer(Age) + 1
```

```
# Estimate Site Index
if (Species=="MAC") {
  ah <- 47.37
  ch <- 1.062
}
if (Species=="LUS") {
  ah <- 38.79
  ch <- 1.099
}
SI <- 0.3 + (ah - 0.3)*(1 - (1 - ((MTH - 0.3)/(ah - 0.3))^(1/ch))^(30/Age))^ch

# Incorporate calibration measurement into thinning table with thinning coefficient of 1
if (N_thins==0) {
  N_thins_cal <- 1
  Thin_age_cal <- as.integer(Age)
  Thin_N_cal <- N
  Thin_k_cal <- 1
} else {

  # Use default thinning coefficient of 0.7 if not specified
  if (missing(Thin_k)) {Thin_k <- rep(0.7,N_thins)}

  N_thins_cal <- N_thins+1
  Thin_age_cal <- c(Thin_age, as.integer(Age))
  Thin_N_cal <- c(Thin_N, N)
  Thin_k_cal <- c(Thin_k, 1)
```

```
}

# Quadratic mean DBH
DBH <- 200*sqrt(BA/(N*pi))

# Estimate 300 Index using the bisection method
I300_lo <- 5
I300_up <- 40
for(j in 1:20) {
  I300_mid <- (I300_lo + I300_up)/2
  Yield_table_lo <- Yield_table(Species, Max_age, I300_lo, SI, Initial_N, N_thins_cal, Thin_age_cal, Thin_N_cal, Thin_k_cal)
  Yield_table_up <- Yield_table(Species, Max_age, I300_up, SI, Initial_N, N_thins_cal, Thin_age_cal, Thin_N_cal, Thin_k_cal)
  Yield_table_mid <- Yield_table(Species, Max_age, I300_mid, SI, Initial_N, N_thins_cal, Thin_age_cal, Thin_N_cal, Thin_k_cal)
  Pred_DBH_lo <- Yield_table_lo[[4]][5][meas_index,] + (Yield_table_lo[[4]][5][meas_index+1,] -
    Yield_table_lo[[4]][5][meas_index,])*(Age - as.integer(Age))
  Pred_DBH_up <- Yield_table_up[[4]][5][meas_index,] + (Yield_table_up[[4]][5][meas_index+1,] -
    Yield_table_up[[4]][5][meas_index,])*(Age - as.integer(Age))
  Pred_DBH_mid <- Yield_table_mid[[4]][5][meas_index,] + (Yield_table_mid[[4]][5][meas_index+1,] -
    Yield_table_mid[[4]][5][meas_index,])*(Age - as.integer(Age))
  flo <- Pred_DBH_lo - DBH
  fup <- Pred_DBH_up - DBH
  fmid <- Pred_DBH_mid - DBH
  if (flo*fmid<0) {I300_up <- I300_mid}
  if (flo*fmid>=0) {I300_lo <- I300_mid}
}
I300 <- I300_mid
```

```
  Yield_table(Species, Max_age, I300, SI, Initial_N, N_thins_cal, Thin_age_cal, Thin_N_cal, Thin_k_cal)

}


# Calibrated yield table examples:


# Unthinned C. macrocarpa stand planted at 1000 stems/ha with a calibration measurement made at age 10.4 years

Calibrated_yield_table(Species="MAC", Age=10.4, N=800, MTH=8.3, BA=25.4, Max_age=65, Initial_N=1000, N_thins=0)


# C. lusitanica stand planted at 1000 stems/ha with a calibration measurement made at age 10.4 years, thinned to 500 stems/ha at age 15 years

Calibrated_yield_table(Species="LUS", Age=10.4, N=800, MTH=8.3, BA=25.4, Max_age=65, Initial_N=1000, N_thins=1, Thin_age=15, Thin_N=500,
Thin_k=0.8)


# C. macrocarpa stand planted at 1200 stems/ha, thinned at ages 10 and 20 years to 700 and 300 stems/ha respectively using default thinning
coefficient,

#   with a calibration measurement made at age 12.1 years

Calibrated_yield_table(Species="MAC", Age=12.1, N=650, MTH=10.5, BA=28.7, Max_age=65, Initial_N=1200, N_thins=2, Thin_age=c(10,20),
Thin_N=c(700,300))
```