# Forest growth and dynamics (practice)

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# Outline

1. Forest growth inputs
2. Running forest growth
3. Evaluation of growth predictions
4. Forest dynamics
5. Forest dynamics including management

M.C. Escher - Up and down, 1947

# 1. Forest growth inputs

# Creating the forest growth input object

We assume we have an appropriate forest object:

```
data(exampleforest)
```

a species parameter data frame:

```
data(SpParamsMED)
```

a soil data frame:

```
examplesoil <- defaultSoilParams(4)
```

and simulation control list:

```
control <- defaultControl("Granier")
```

With these four elements we can build our input object for function `growth()`:

```
x <- forest2growthInput(exampleforest, examplesoil, SpParamsMED, control)
```

# Structure of the growth input object (1)

The growth input object is a `list` with several elements:

```r
names(x)
```

```
 [1] "control"                    "soil"                      
 [3] "snowpack"                   "canopy"                    
 [5] "herbLAI"                    "herbLAImax"                
 [7] "cohorts"                    "above"                     
 [9] "below"                      "belowLayers"               
[11] "paramsPhenology"            "paramsAnatomy"             
[13] "paramsInterception"         "paramsTranspiration"       
[15] "paramsWaterStorage"         "paramsGrowth"              
[17] "paramsMortalityRegeneration" "paramsAllometries"         
[19] "internalPhenology"          "internalWater"             
[21] "internalLAIDistribution"    "internalCarbon"            
[23] "internalAllocation"         "internalMortality"         
[25] "internalFCCS"              
```

Element `above` contains the above-ground structure data that we already know, but with an additional column `SA` that describes the estimated initial amount of *sapwood area*:

```
        SP        N   DBH Cover   H        CR          SA   LAI_live
T1_148 148 168.0000 37.55    NA 800 0.6605196 383.4520992 0.84874773
T2_168 168 384.0000 14.60    NA 660 0.6055642  47.0072886 0.70557382
S1_165 165 749.4923    NA  3.75  80 0.8032817   0.9753929 0.03062604
       LAI_expanded LAI_dead LAI_nocomp    Loading ObsID
T1_148   0.84874773        0 1.29720268 0.32447403  <NA>
T2_168   0.70557382        0 1.01943205 0.20102636  <NA>
S1_165   0.03062604        0 0.04412896 0.01407945  <NA>
```

# Structure of the growth input object (2)

Elements starting with `params*` contain cohort-specific model parameters. An important set of parameters are in `paramsGrowth`:

```
          RERleaf RERsapwood  RERfineroot CCleaf CCsapwood CCfineroot
T1_148 0.01210607   5.15e-05 0.0009610199 1.5905      1.47        1.3
T2_168 0.01757808   5.15e-05 0.0072846640 1.4300      1.47        1.3
S1_165 0.02647746   5.15e-05 0.0072846640 1.5320      1.47        1.3
       RGRleafmax RGRsapwoodmax RGRcambiummax RGRfinerootmax SRsapwood
T1_148       0.09            NA   0.002628095            0.1  0.000135
T2_168       0.09            NA   0.002500000            0.1  0.000135
S1_165       0.09         0.002            NA            0.1  0.000135
        SRfineroot      RSSG fHDmin fHDmax     WoodC
T1_148 0.001897231 0.3725000     80    160 0.4979943
T2_168 0.001897231 0.9500000     40    100 0.4740096
S1_165 0.001897231 0.7804035     NA     NA 0.4749178
```

Elements starting with `internal*` contain state variables required to keep track of plant status. For example, the metabolic and storage carbon levels can be seen in `internalCarbon`:

```
       sugarLeaf starchLeaf sugarSapwood starchSapwood
T1_148 0.4029239 0.00925123    0.5738487      3.201897
T2_168 0.3585751 0.00925123    1.0741383      3.100817
S1_165 0.7223526 0.00925123    0.2857655      2.654773
```

# 2. Forest growth

# Forest growth run

The call to function `growth()` needs the growth input object, the weather data frame, latitude and elevation:

```r
G <- growth(x, examplemeteo, latitude = 41.82592, elevation = 100)
```

```
Initial plant cohort biomass (g/m2): 5068.34
Initial plant water content (mm): 4.73001
Initial soil water content (mm): 290.875
Initial snowpack content (mm): 0
Performing daily simulations

 Year 2001:............

Final plant biomass (g/m2): 5256.53
Change in plant biomass (g/m2): 188.193
Plant biomass balance result (g/m2): 188.193
Plant biomass balance components:
  Structural balance (g/m2) 104 Labile balance (g/m2) 92
  Plant individual balance (g/m2) 196 Mortality loss (g/m2) 8
Final plant water content (mm): 4.73794
Final soil water content (mm): 274.787
Final snowpack content (mm): 0
Change in plant water content (mm): 0.00793033
Plant water balance result (mm): -0.00116903
Change in soil water content (mm): -16.0878
Soil water balance result (mm): -16.0878
Change in snowpack water content (mm): 0
Snowpack water balance result (mm): 7.10543e-15
Water balance components:
  Precipitation (mm) 513 Rain (mm) 462 Snow (mm) 51
```

# Growth output object

Function `growth()` returns an object of class with the same name, actually a list:

```
class(G)
```

```
[1] "growth" "list"
```

… whose elements are:

```
names(G)
```

```
 [1] "latitude"             "topography"          "weather"
 [4] "growthInput"          "growthOutput"        "WaterBalance"
 [7] "CarbonBalance"        "BiomassBalance"      "Soil"
[10] "Snow"                 "Stand"               "Plants"
[13] "LabileCarbonBalance" "PlantBiomassBalance" "PlantStructure"
[16] "GrowthMortality"
```

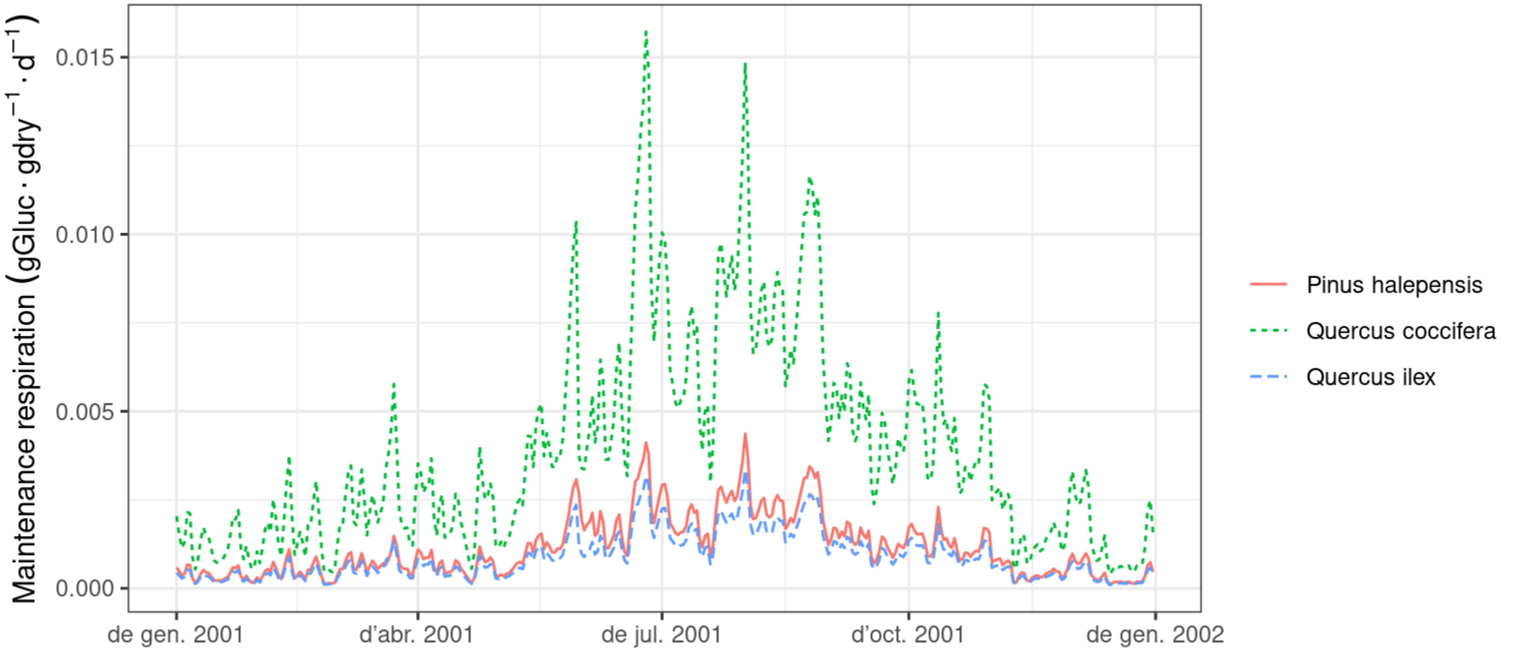
| Elements | Information |
|---|---|
| `latitude`, `topography`, `weather`, `growthInput` | Copies of the information used in the call to `growth()` |
| `growthOutput` | State variables at the end of the simulation (can be used as input to a subsequent one) |
| `WaterBalance`, `Soil`, `Snow`, `Stand`, `Plants` | [same as `spwb` …] |
| `CarbonBalance` | Stand-level carbon blance |
| `LabileCarbonBalance` | Components of the individual-level labile carbon balance |
| `PlantBiomassBalance` | Components of indvidual- and cohort-level biomass balance |
| `PlantStructure` | Structural variables (DBH, height, sapwood area…) |
| `GrowthMortality` | Growth and mortality rates |

# Post-processing

Users can inspect the output of `growth()` simulations using functions `extract()`, `summary()` and `plot()` on the simulation output.

Several new plots are available in addition to those available for `spwb()` simulations (see `?plot.growth`). For example:

```
plot(G, "MaintenanceRespiration", bySpecies = TRUE)
```




… but instead of typing all plots, we can call the interactive plot function `shinyplot()`.

# 3. Evaluation of growth predictions

# Observed data frame

Evaluation of growth simulations will normally imply the comparison of predicted vs observed **basal area increment** (BAI) or **diameter increment** (DI) at a given temporal resolution.

Here, we illustrate the evaluation functions included in the package using a fake data set at *daily* resolution, consisting on the predicted values and some added error.

```r
data(exampleobs)
head(exampleobs)
```

```
       dates       SWC       ETR    E_T1_148   E_T2_168 FMC_T1_148 FMC_T2_168
1 2001-01-01 0.3007733 2.2436218 0.09187857 0.14142950   125.9071   93.07915
2 2001-01-02 0.3091627 2.3236565 0.26480973 0.19095008   125.9137   93.07863
3 2001-01-03 0.2996498 0.7409083 0.15345643 0.17546363   125.8760   93.10512
4 2001-01-04 0.3042764 1.7173522 0.23470647 0.04643454   125.8643   93.07022
5 2001-01-05 0.3054886 2.0002562 0.37687792 0.10623552   125.8493   93.08487
6 2001-01-06 0.3062005 2.0722706 0.16342360 0.05550329   125.9367   93.07343
    BAI_T1_148 BAI_T2_168    DI_T1_148 DI_T2_168
1 6.222625e-06          0 9.948881e-08         0
2 3.091274e-10          0 1.071090e-11         0
3 1.298482e-13          0 0.000000e+00         0
4 2.886195e-11          0 5.552753e-13         0
5 1.287020e-03          0 1.367289e-05         0
6 1.471202e-03          0 1.000411e-05         0
```

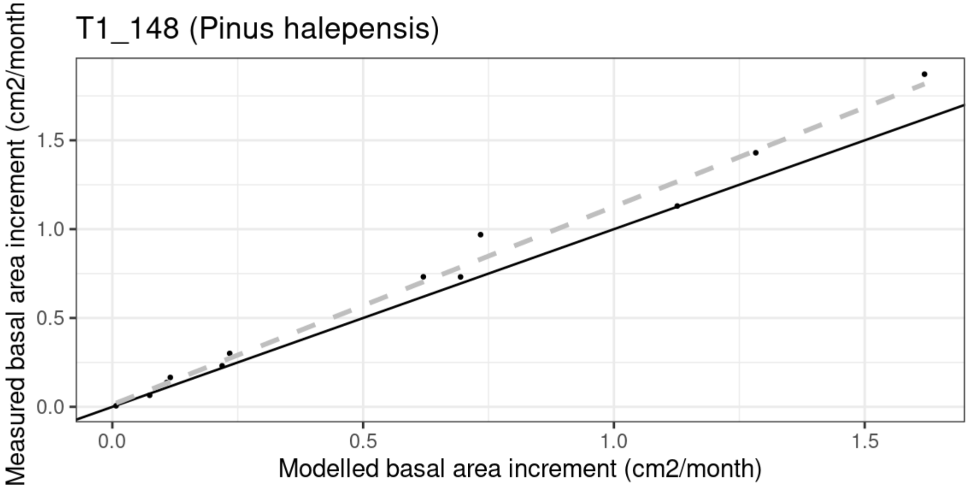
To specify observed growth data at *monthly* or *annual scale*, you should specify the first day of each month/year (e.g. `2001-01-01`, `2002-01-01`, etc for years) as row names in your observed data frame.

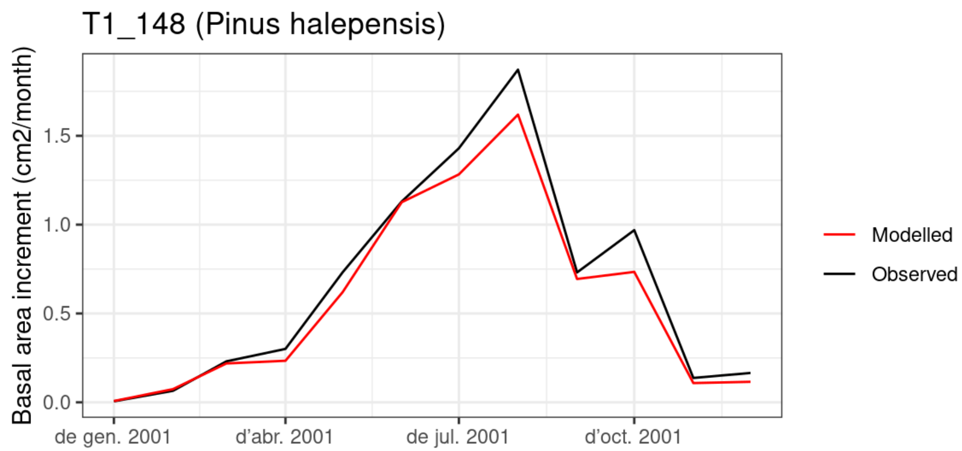
# Evaluation plot

Assuming we want to evaluate the predictive capacity of the model in terms of monthly basal area increment for the *pine cohort* (i.e. `T1_148`), we can plot the relationship between observed and predicted values using `evaluation_plot()`:

```
evaluation_plot(G, exampleobs, "BAI",
                cohort = "T1_148",
                temporalResolution = "month",
                plotType = "scatter")
```

```
evaluation_plot(G, exampleobs, "BAI",
                cohort = "T1_148",
                temporalResolution = "month",
                plotType = "dynamics")
```




Using `temporalResolution = "month"` we indicate that simulated and observed data should be temporally aggregated to conduct the comparison.

The following code would help us quantifying the *strength* of the relationship:

```
evaluation_stats(G, exampleobs, "BAI", cohort = "T1_148", temporalResolution = "month")
```

```
          n        Bias     Bias.rel          MAE      MAE.rel            r
12.00000000 -0.07781339 -12.01831387   0.07962106  12.29751007   0.99395791
        NSE     NSE.abs
 0.95935190  0.83966426
```

# 4. Forest dynamics

# Forest dynamics run

## Weather preparation

In this vignette we will fake a three-year weather input by repeating the example weather data frame four times:

```
meteo <- rbind(examplemeteo, examplemeteo, examplemeteo, examplemeteo)
```

we need to update the dates in row names so that they span four consecutive years:

```
meteo$dates <- seq(as.Date("2001-01-01"),
                   as.Date("2004-12-30"), by="day")
```

## Simulation

The call to `fordyn()` has the following form:

```
fd<-fordyn(exampleforest, examplesoil, SpParamsMED, meteo, control,
           latitude = 41.82592, elevation = 100)
```

```
Simulating year 2001 (1/4):  (a) Growth/mortality, (b) Regeneration nT = 2 nS = 1
Simulating year 2002 (2/4):  (a) Growth/mortality, (b) Regeneration nT = 2 nS = 1
Simulating year 2003 (3/4):  (a) Growth/mortality, (b) Regeneration nT = 2 nS = 1
Simulating year 2004 (4/4):  (a) Growth/mortality, (b) Regeneration nT = 2 nS = 1
```

**Important**

- `fordyn()` operates on `forest` objects directly, instead of using an intermediary object (such as `spwbInput` and `growthInput`).
- `fordyn()` calls function `growth()` internally for each simulated year, but all console output from `growth()` is hidden.

# Forest dynamics output (1)

As with other models, the output of `fordyn()` is a list, which has the following elements:

| **Elements** | **Information** |
|---|---|
| `StandSummary`, `SpeciesSummary`, `CohortSummary` | *Annual* summary statistics at different levels |
| `TreeTable`, `ShrubTable` | Structural variables of **living** cohorts at each annual time step. |
| `DeadTreeTable`, `DeadShrubTable` | Structural variables of **dead** cohorts at each annual time step |
| `CutTreeTable`, `CutShrubTable` | Structural variables of **cut** cohorts at each annual time step |
| `ForestStructures` | Vector of `forest` objects at each time step. |
| `GrowthResults` | Result of internally calling `growth()` at each time step. |
| `ManagementArgs` | Management arguments for a subsequent call to `fordyn()`. |
| `NextInputObject`, `NextForestObject` | Objects `growthInput` and `forest` to be used in a subsequent call to `fordyn()`. |

# Forest dynamics output (2)

For example, we can compare the initial `forest` object with the final one:

```r
exampleforest
```

```
$treeData
           Species   N   DBH Height Z50  Z95
1 Pinus halepensis 168 37.55    800 100  600
2     Quercus ilex 384 14.60    660 300 1000

$shrubDataData
            Species Cover Height Z50  Z95
1 Quercus coccifera  3.75     80 200 1000

$herbCover
[1] 10

$herbHeight
[1] 20

$seedBank
[1] Species Percent
<0 files> (o «row.names» de longitud 0)

attr(,"class")
[1] "forest" "list"
```

```r
fd$NextForestObject
```

```
$treeData
           Species      DBH   Height        N Z50  Z95
1 Pinus halepensis 38.01410 824.7217 166.7796 100  600
2     Quercus ilex 15.04679 673.8471 382.6513 300 1000

$shrubData
            Species  Height    Cover Z50  Z95
1 Quercus coccifera 75.4552 3.237287 200 1000

$herbCover
[1] 10

$herbHeight
[1] 20

$seedBank
            Species Percent
1  Pinus halepensis     100
2      Quercus ilex     100
3 Quercus coccifera     100

attr(,"class")
[1] "forest" "list"
```

# Forest dynamics output (3)

The output includes **summary statistics** that describe the structural and compositional state of the forest corresponding to *each annual time step*.

For example, we can access *stand-level* statistics using:

```
fd$StandSummary
```

```
  Step NumTreeSpecies NumTreeCohorts NumShrubSpecies NumShrubCohorts
1    0              2              2               1               1
2    1              2              2               1               1
3    2              2              2               1               1
4    3              2              2               1               1
5    4              2              2               1               1
  TreeDensityLive TreeBasalAreaLive DominantTreeHeight DominantTreeDiameter
1        552.0000          25.03330           800.0000             37.55000
2        551.3663          25.20814           806.2122             37.66571
3        550.7269          25.38313           812.4144             37.78185
4        550.0818          25.55825           818.5877             37.89804
5        549.4309          25.73303           824.7217             38.01410
  QuadraticMeanTreeDiameter HartBeckingIndex ShrubCoverLive BasalAreaDead
1                  24.02949         53.20353       3.750000    0.00000000
2                  24.12711         52.82391       3.092051    0.03917375
3                  24.22476         52.45105       3.139858    0.03983747
4                  24.32243         52.08602       3.188231    0.04050957
5                  24.41991         51.72923       3.237287    0.04118879
  ShrubCoverDead BasalAreaCut ShrubCoverCut
1    0.000000000            0             0
2    0.005308898            0             0
3    0.004784468            0             0
4    0.004858342            0             0
5    0.004933117            0             0
```

# Forest dynamics output (4)

Another useful output of `fordyn()` are tables in long format with cohort structural information (i.e. DBH, height, density, etc) for each time step:

```
fd$TreeTable
```

```
   Step Year Cohort          Species      DBH   Height        N Z50  Z95 ObsID
1     0   NA T1_148 Pinus halepensis 37.55000 800.0000 168.0000 100  600  <NA>
2     0   NA T2_168     Quercus ilex 14.60000 660.0000 384.0000 300 1000  <NA>
3     1 2001 T1_148 Pinus halepensis 37.66571 806.2122 167.6992 100  600  <NA>
4     1 2001 T2_168     Quercus ilex 14.71218 663.4915 383.6671 300 1000  <NA>
5     2 2002 T1_148 Pinus halepensis 37.78185 812.4144 167.3956 100  600  <NA>
6     2 2002 T2_168     Quercus ilex 14.82389 666.9588 383.3314 300 1000  <NA>
7     3 2003 T1_148 Pinus halepensis 37.89804 818.5877 167.0890 100  600  <NA>
8     3 2003 T2_168     Quercus ilex 14.93552 670.4135 382.9928 300 1000  <NA>
9     4 2004 T1_148 Pinus halepensis 38.01410 824.7217 166.7796 100  600  <NA>
10    4 2004 T2_168     Quercus ilex 15.04679 673.8471 382.6513 300 1000  <NA>
```

**Note**

The `NA` values in `Year` correspond to the initial state.

# Forest dynamics output (5)

The same information can be shown for trees that are predicted to die during each simulated year:

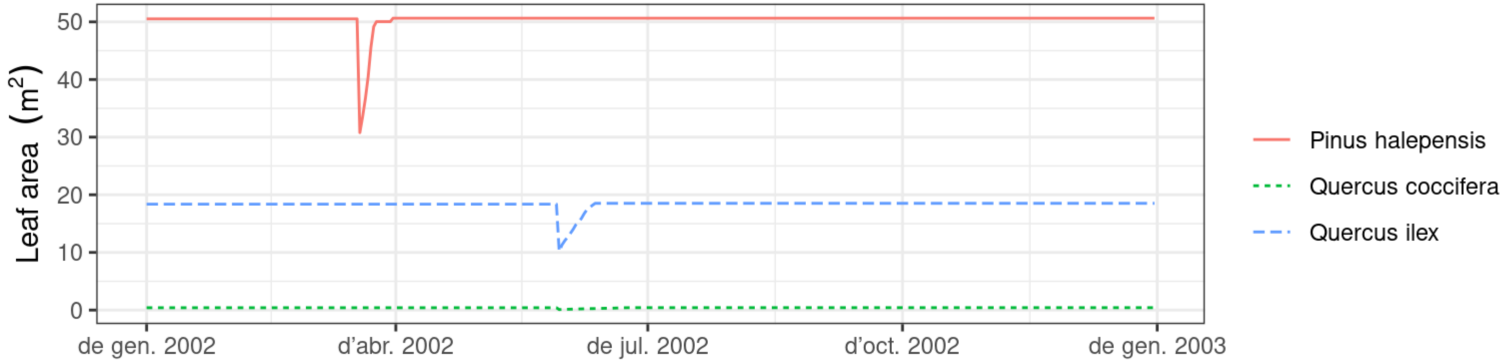
```r
fd$DeadTreeTable
```

```
  Step Year Cohort          Species      DBH   Height         N N_starvation
1    1 2001 T1_148 Pinus halepensis 37.66571 806.2122 0.3007828            0
2    1 2001 T2_168      Quercus ilex 14.71218 663.4915 0.3328893            0
3    2 2002 T1_148 Pinus halepensis 37.78185 812.4144 0.3036481            0
4    2 2002 T2_168      Quercus ilex 14.82389 666.9588 0.3357419            0
5    3 2003 T1_148 Pinus halepensis 37.89804 818.5877 0.3065253            0
6    3 2003 T2_168      Quercus ilex 14.93552 670.4135 0.3386082            0
7    4 2004 T1_148 Pinus halepensis 38.01410 824.7217 0.3094089            0
8    4 2004 T2_168      Quercus ilex 15.04679 673.8471 0.3414828            0
  N_dessication N_burnt Z50  Z95 ObsID
1             0       0 100  600  <NA>
2             0       0 300 1000  <NA>
3             0       0 100  600  <NA>
4             0       0 300 1000  <NA>
5             0       0 100  600  <NA>
6             0       0 300 1000  <NA>
7             0       0 100  600  <NA>
8             0       0 300 1000  <NA>
```

# Post-processing

Accessing elements of `GrowthResults`, we can extract, summarize or plot simulation results for a particular year:

```
plot(fd$GrowthResults[[2]], "LeafArea", bySpecies = TRUE)
```




It is also possible to plot the whole series of results by passing a `fordyn` object to the `plot()` function:

```
plot(fd, "LeafArea", bySpecies = TRUE)
```


Finally, we can create interactive plots using function `shinyplot()`, in the same way as with other simulations.

# 5. Forest dynamics including management

# Running simulations with management

`fordyn()` allows the user to supply an *arbitrary* function implementing a desired management strategy for the stand whose dynamics are to be simulated.

The package includes an in-built default function called `defaultManagementFunction()` along management parameter defaults provided by function `defaultManagementArguments()`.

To run simulations with management we need to define (and modify) management arguments…

```
# Default arguments
args <- defaultManagementArguments()
# Here one can modify defaults before calling fordyn()
#
```

… and call `fordyn()` specifying the management function and its arguments:

```
fd<-fordyn(exampleforest, examplesoil, SpParamsMED, meteo, control,
           latitude = 41.82592, elevation = 100,
           management_function = defaultManagementFunction,
           management_args = args)
```

When management is included, tables `CutTreeTable` and `CutShrubTable` will contain extraction data:

```
fd$CutTreeTable
fd$CutShrubTable
```

# Forest management parameters (1)

Function `defaultManagementArguments()` returns a list with default values for *management parameters* to be used in conjunction with `defaultManagementFunction()`:

| Element | Description |
|---|---|
| `type` | Management model, either ‘regular’ or ‘irregular’ |
| `targetTreeSpecies` | Either `"all"` for unspecific cuttings or a numeric vector of target tree species to be selected for cutting operations |
| `thinning` | Kind of thinning to be applied in irregular models or in regular models before the final cuts. Options are `"below"`, `"above"`, `"systematic"`, `"below-systematic"`, `"above-systematic"` or a string with the proportion of cuts to be applied to different diameter sizes |
| `thinningMetric` | The stand-level metric used to decide whether thinning is applied, either `"BA"` (basal area), `"N"` (density) or `"HB"` (Hart-Becking index) |
| `thinningThreshold` | The threshold value of the stand-level metric causing the thinning decision |
| `thinningPerc` | Percentage of stand’s basal area to be removed in thinning operations |
| `minThinningInterval` | Minimum number of years between thinning operations |
| `finalMeanDBH` | Mean DBH threshold to start final cuts |
| `finalPerc` | String with percentages of basal area to be removed in final cuts, separated by ‘-’ (e.g. “40-60-100”) |
| `finalYearsBetweenCuts` | Number of years separating final cuts |

# Forest management parameters (2)

The same list includes *state variables* for management (these are modified during the simulation):

| Element | Description |
|---|---|
| `yearsSinceThinning` | State variable to count the years since the last thinning ocurred |
| `finalPreviousStage` | Integer state variable to store the stage of final cuts ('0' before starting final cuts) |
| `finalYearsToCut` | State variable to count the years to be passed before new final cut is applied. |

**Tip**

Instead of using the in-built management function, you could code your own management function and specify its own set of parameters!

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