# Overview of forest models and simulators as a support to sustainable forest management in a global change context

## ▪Why do we need forest growth models?

**To support the increasingly complex forest management…**

- Forestry and forest management

# ▪Forestry

✓ Forestry is the science, art, business, and practice of conserving and managing forests and forest lands in a way that

- provide a sustained supply of forest products
- maintain the forest health and vitality
- provide any other forest values desired by the forest owners

**This is a "traditional" definition**

(adapted from Ford-Robertson, 1971)

# ▪Forestry

✓ Forestry is the science, art, business, and practice of conserving and managing forests and forest lands in a way that

– maintain their health and vitality

– provide a sustained supply of **ecosystem services** desired by the forest owners and the **society** in general

– are **resilient** to the increasing occurrence of **hazards**

– are adaptable to **climate change**

(modified from Ford-Robertson, 1971)

Forestry implies decisions about the relationship between the man and the forest, in particular about the way man modifies the forest in order to achieve the desired objectives

↓

**FOREST MANAGEMENT**

# Forest management decisions are not easy…

- Every forest activity, undertaken at any point in time has impacts on its future health and vitality and on the ecosystem services provided over time
- There is no optimum sequence of silvicultural operations, they depend on the objective for each stand and landscape (there are no “recipes”)
- Objectives may change over time (and have changed during the last decades…)
- Many times there is the need to take into account rules established at a higher level (e.g. forest policy) in the day to day management

Forest management decisions

↓

The need to evaluate, on the long term, the impact of alternative management options under a changing environment

↓

# FOREST GROWTH MODELS

# ▪Evolution of Forestry

| Stage of development | | Result |
|---|---|---|
| Preforestry – exploitation | → | Resource depletion |
| Administrative forestry (timber oriented) | → | Failure to achieve conservation and sustainability goals |
| Ecologically-based forestry (considering the ecosystem as a whole) | → | Sustained production of timber achieved by an ecology based management |
| Social and ecologically-based forestry (emphasis on all ecosystem services) | → | Ecologically based forestry that sustains a wide range of forest conditions and values desired by society |



(adapted from Kimmins, 1997)

# ▪Evolution of forestry and forest management

- ✓ The evolution of forestry made the interaction between man and the forest – forest management – more and more difficult
- ✓ Forest management is nowadays not an easy task...
- ✓ In 2000 multifunctional sustainable forest management (MCPFC) was in the order of the day:
  - – Pan-European (and other) criteria and indicators / certification schemes came to the agenda

# ▪Evolution of forestry and forest management

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  - – Pan-European (and other) criteria and indicators / certification schemes came to the agenda
- ✓ The importance of ecosystem services became relevant

# ▪Ecosystem services

✓ Ecosystem services are the benefices that nature provides to man and that are essential for man survival, being associated with the quality of life and welfare of society:

- Forests provide wood, food, medicinal substances and fibers, purify water, regulate climate and produce genetic resources
- Protection against natural disasters, erosion control, pollination, fertilization of soil by animal feces, decomposition of animals and plants by microorganisms
- Fluvial systems offer fresh water, energy and recreation
- The wet coastal areas filter residues, mitigate floods and serve as a nursery for commercial fishing

# Ecosystem services

| Provisioning | Regulating | Cultural |
|---|---|---|
| Products produced by the ecosystems | Benefices resulting from the regulation of ecosystem processes | Non-material benefices provided by ecosystems |
| ▪ Food<br>▪ Fresh water<br>▪ Material for energy production<br>▪ Wood and Fiber<br>▪ Biochemical and genetic resources<br>▪ Non-wood products | ▪ Climate control<br>▪ Purification of water and air<br>▪ Regulation of the water cycle<br>▪ Erosion control<br>▪ Control of floods<br>▪ Control of pests and diseases | ▪ Recreation<br>▪ Science and education<br>▪ Aestethical<br>▪ Spiritual |

## Supporting

Services needed for the production of all the other services

▪ cycle of nutrients ▪ soil formation ▪ primary production

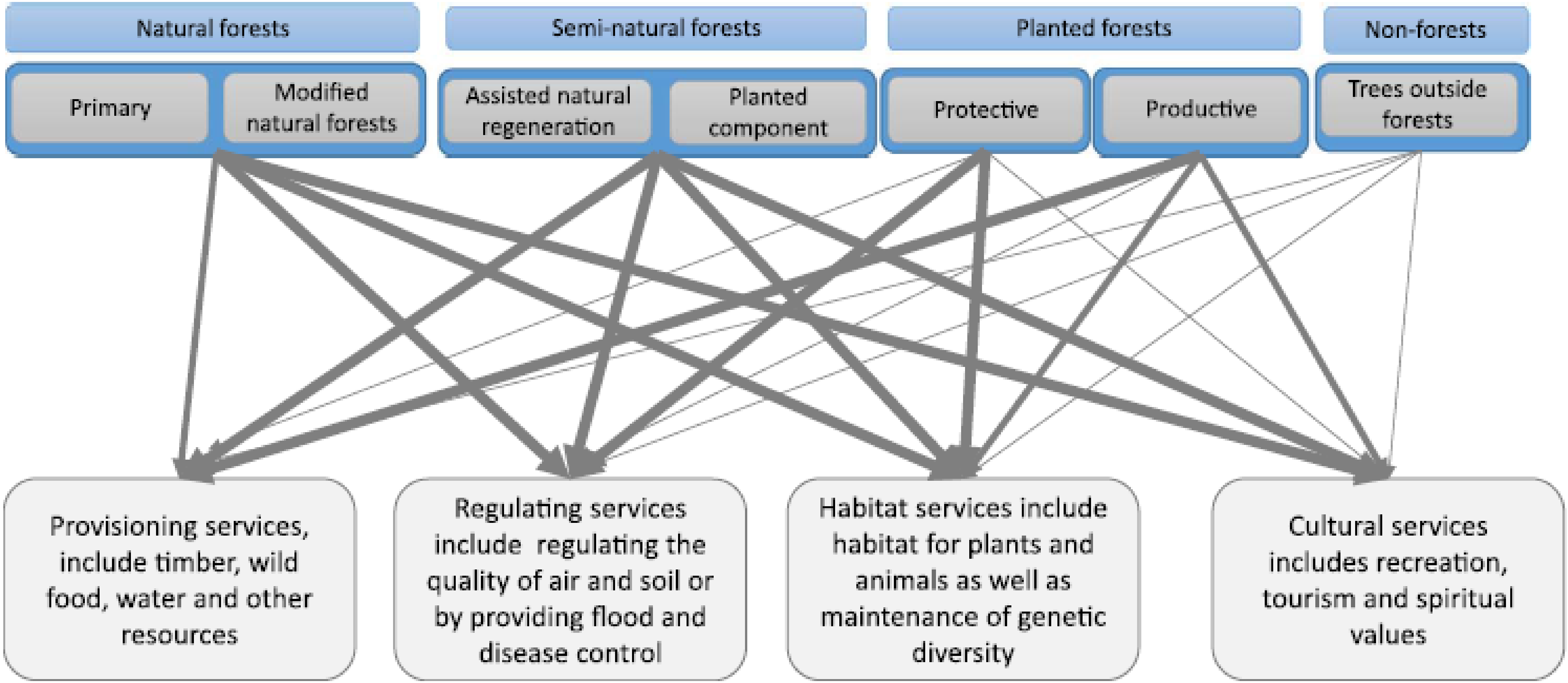
▪ Polinization and seed dispersal

# ▪Primary and secondary forests, planted forests

✓ Forests can be classified according to the level of human intervention they undergo:

- **Primary forests**: untouched
- **Secondary forests**: recovering from human disturbances, either naturally or by afforestation and/or reforestation activities
- **Planted forests**: at maturity are predominantly composed of trees established through planting and/or deliberate seeding
- **Plantation forests**: intensively managed, at maturity composed of one or two species, one age class, regular tree spacing

# ▪Ecosystem services from different intensities of management

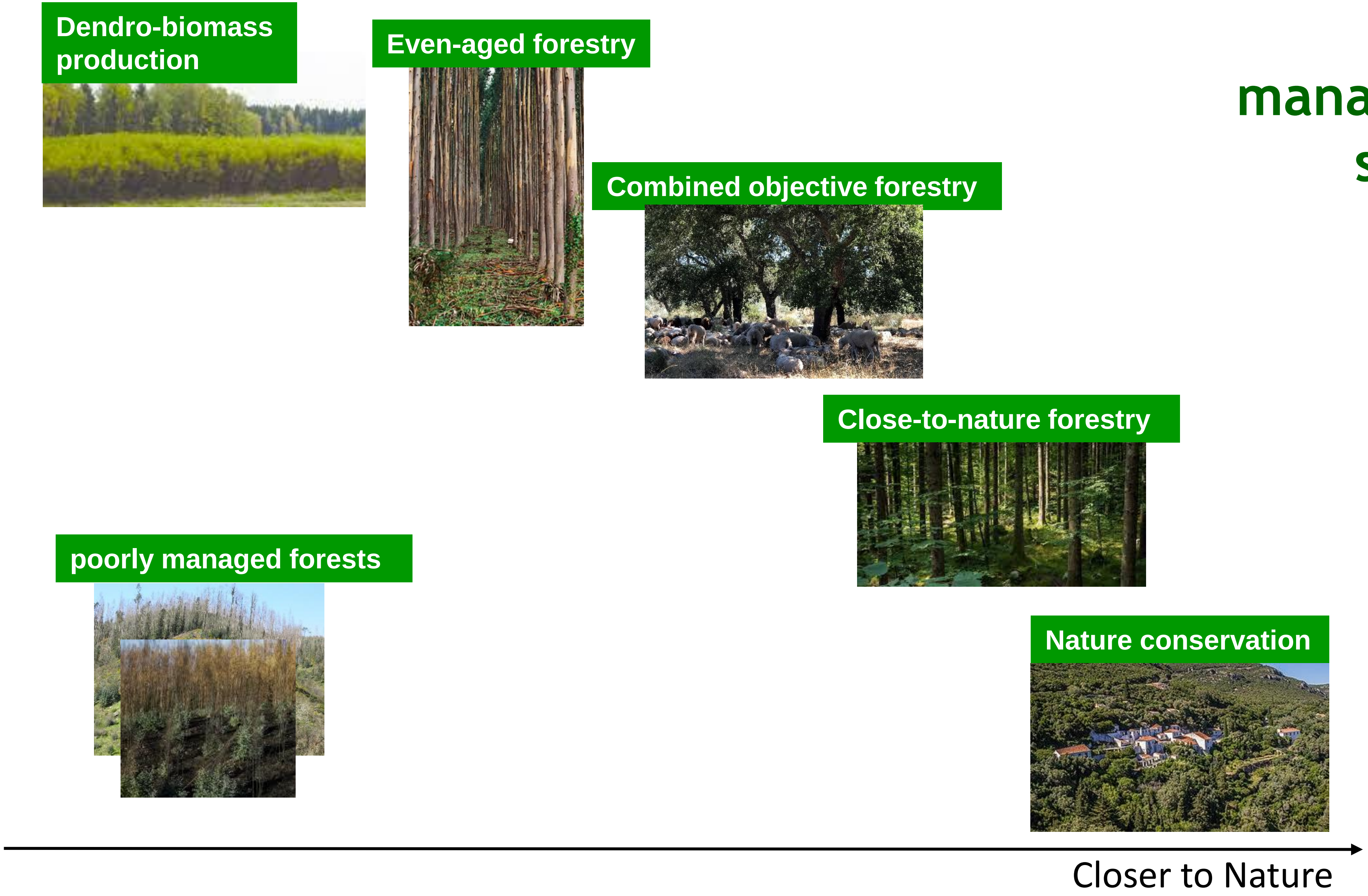




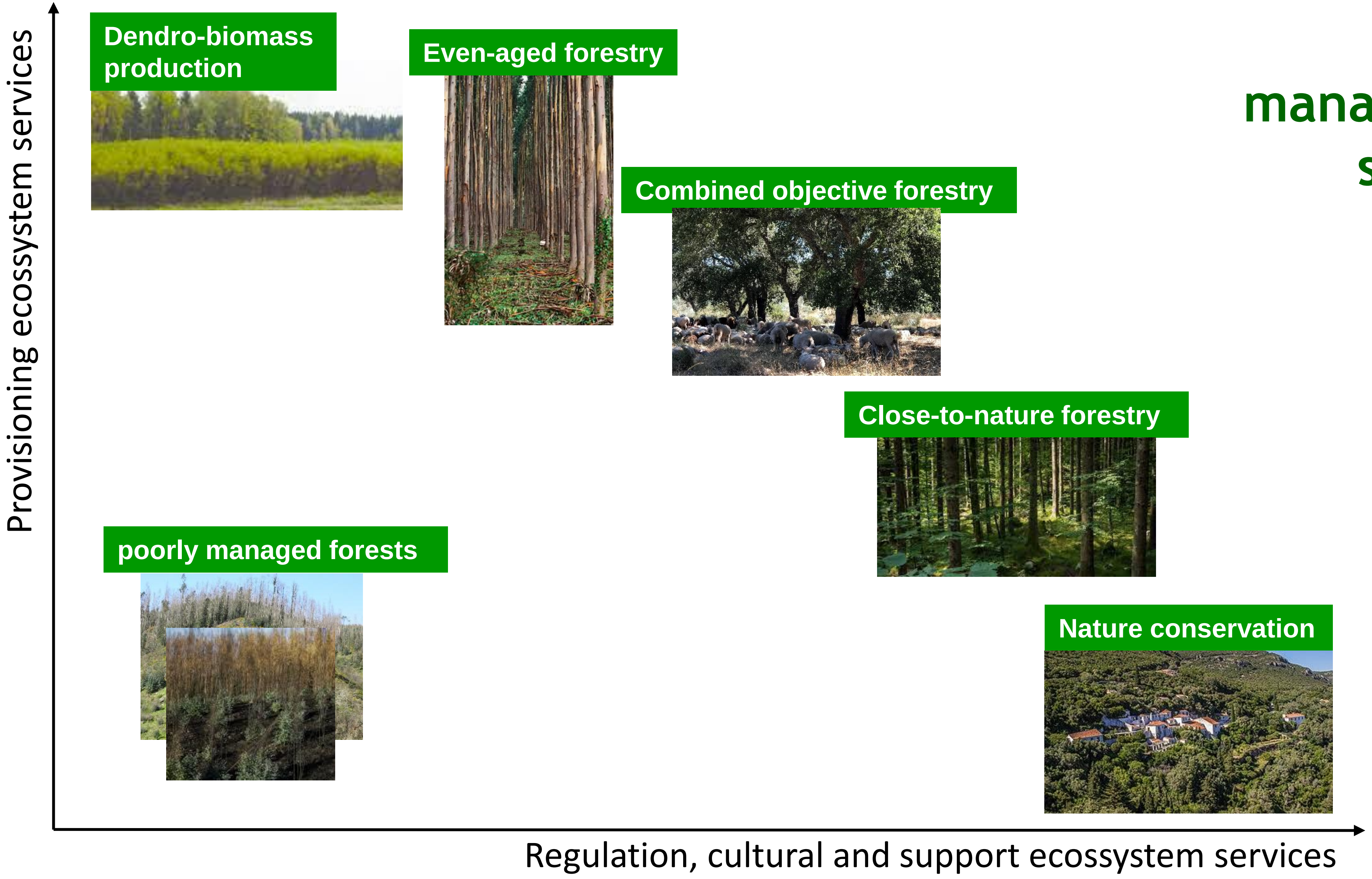

Adapted from Baral et al. 2016

## ▪Trade-offs in forest management at stand level

# Forest management at stand level



# Forest management at stand level



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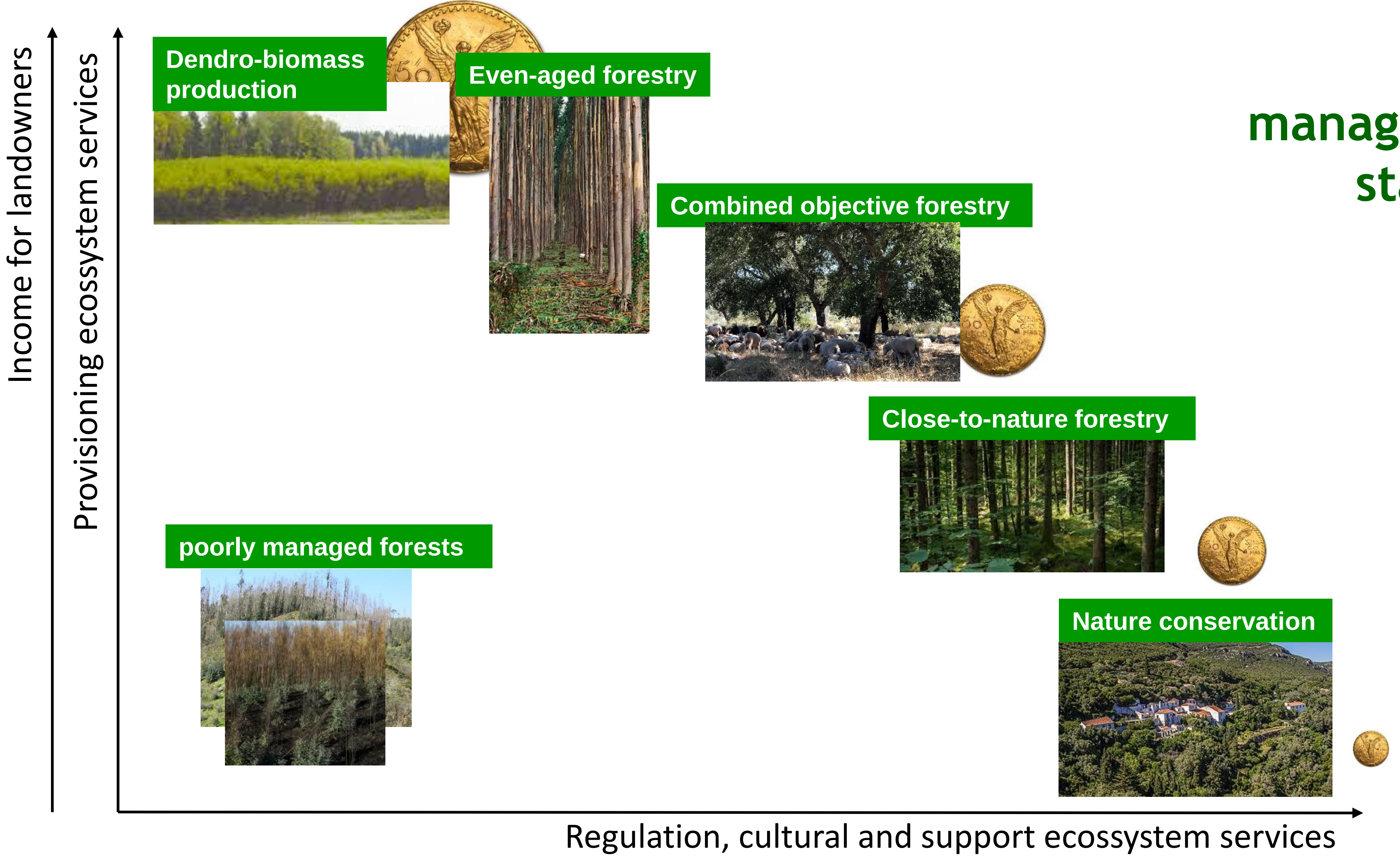

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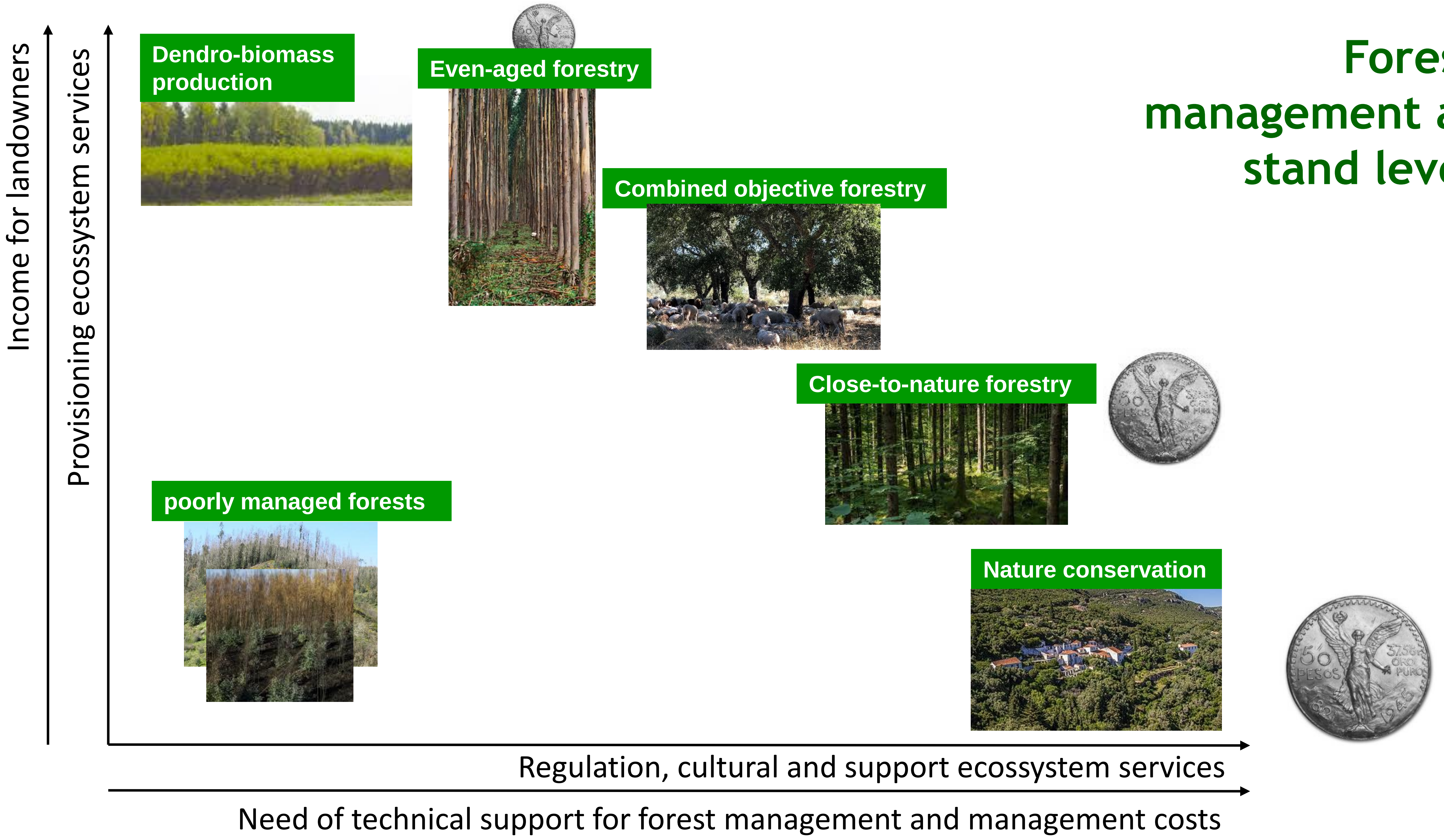

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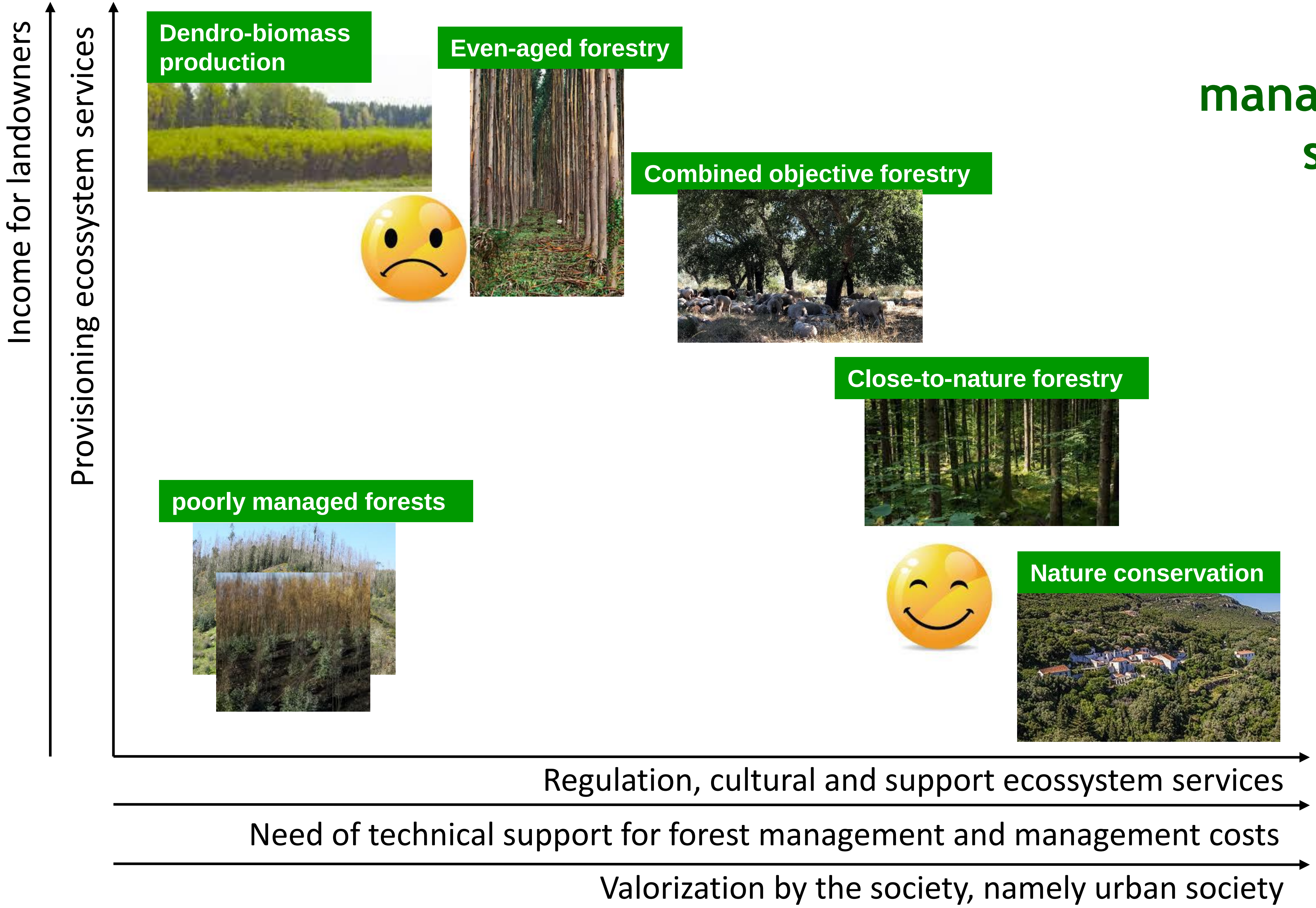


- Forest models support decisions in such a complex environment!

# ▪Components of forest models and simulators

# ▪Forest model (Cost Action FP0603 terminology)

- ✓ A dynamic representation of the forest and its behaviour (at whatever level of complexity)
- ✓ The forest is defined by the values of a set of state variables (N, hdom, G, V, W, Wshrubs, soil characteristics, etc)
- ✓ The model is able to simulate the evolution of forests over time (evolution of state variables) and its responses to changes in the driving variables
- ✓ The model is based a set of (sub-)models or modules that together determine the behaviour of the forest

## ▪State variables (Cost Action FP0603 terminology)

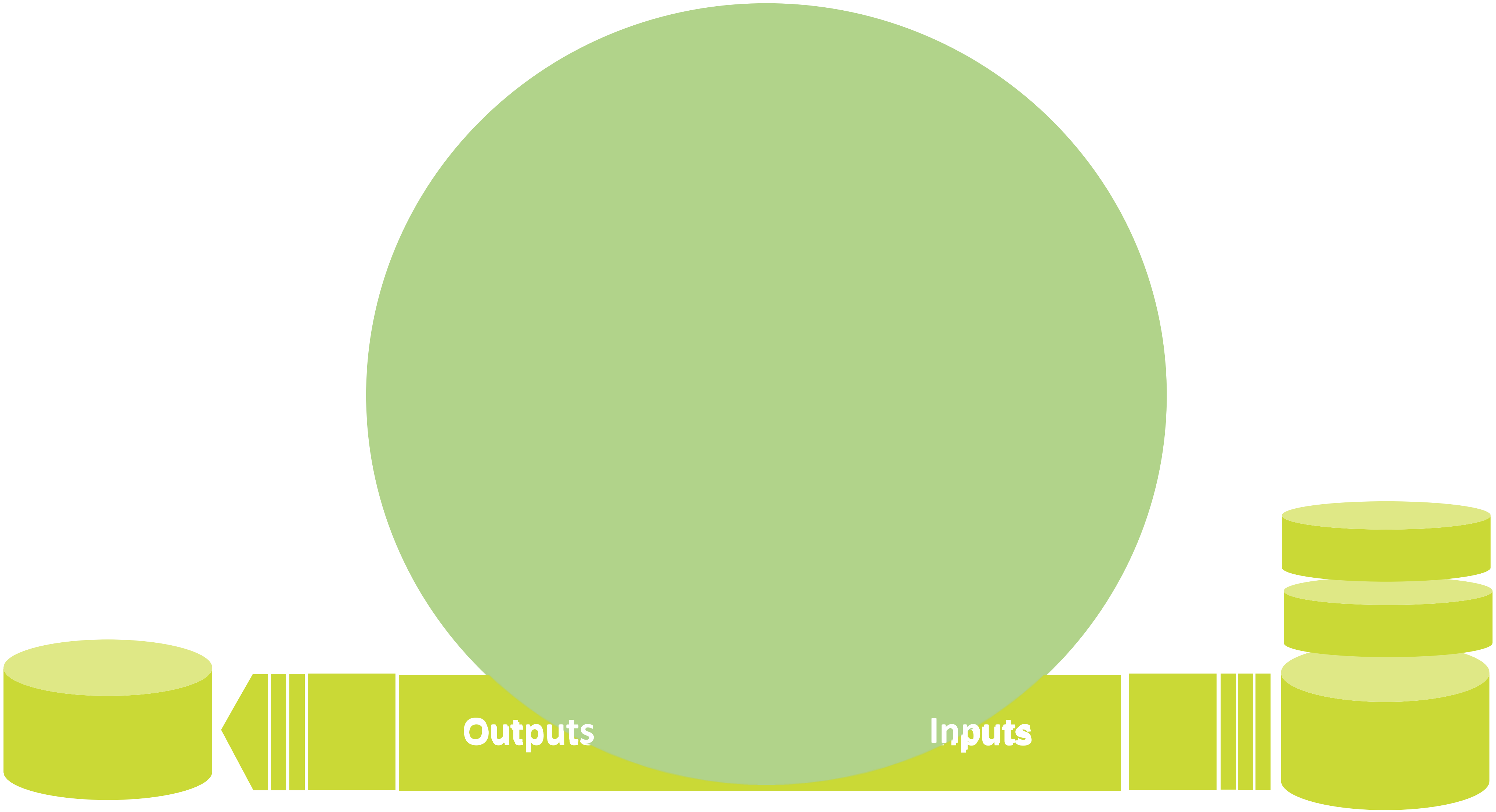
- ✓ Set of variables (stand and/or tree variables or some ecosystem pools) that characterize the forest at a given moment and whose evolution in time is the result (output) of the model:
  - – Principal variables if they are part of the growth modules
  - – Derived variables if they are indirectly computed from the values of the principal variables
- ✓ Model module
  - – Set of equations and/or procedures that led to the prediction of the future value of a state variable

# ▪State variables (Cost Action  FP0603 terminology)

✓ Depending on the type of model, the same state variable can be principal in one model but derived in another one. For instance:

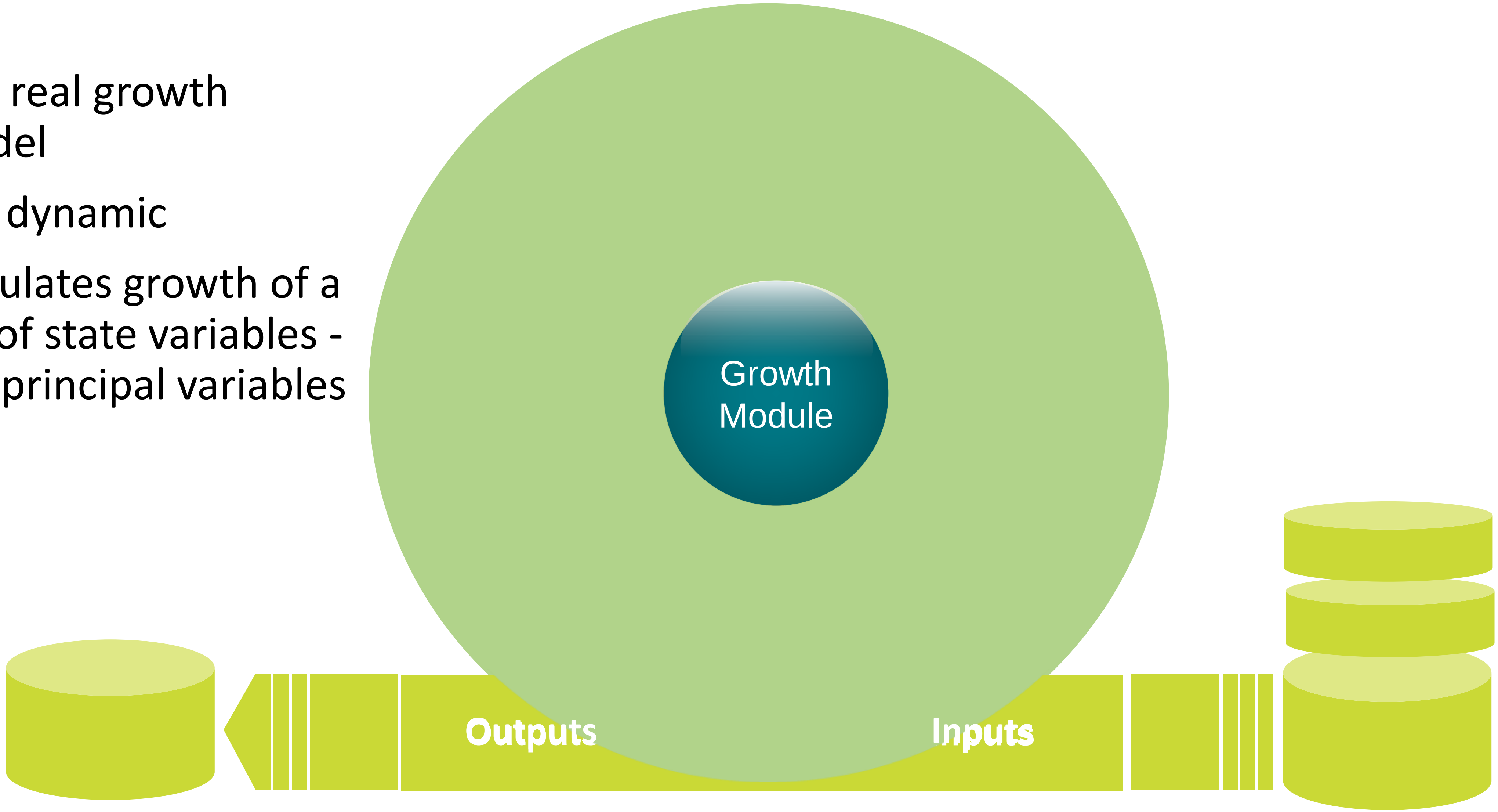
- **Dominant height** is usually a principal variable in empirical models, namely for even-aged pure stands, but it is usually derived in process-based models
- **Basal area** is a principal variable in whole stand empirical models but it is derived in individual tree models where the "equivalent" principal variable are the **diameters** of each individual tree
- Principal variables in process based models are mainly the **biomass pools** (ate stand or tree level) and not the "traditional" stand variables

# ▪Forest model



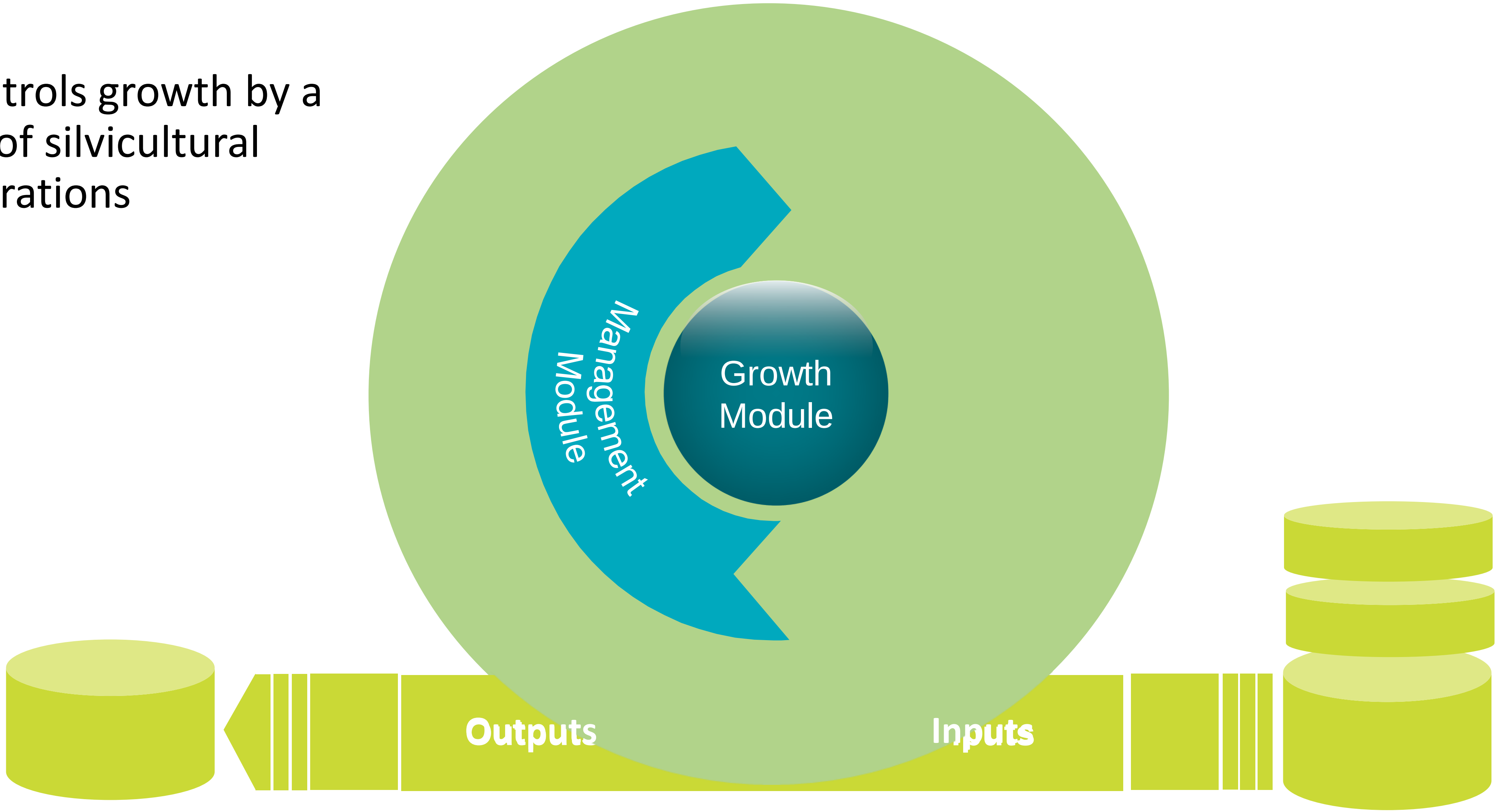
# ▪Forest model

- ✓The real growth model
- ✓It is dynamic
- ✓Simulates growth of a set of state variables - the principal variables



# ▪Forest model

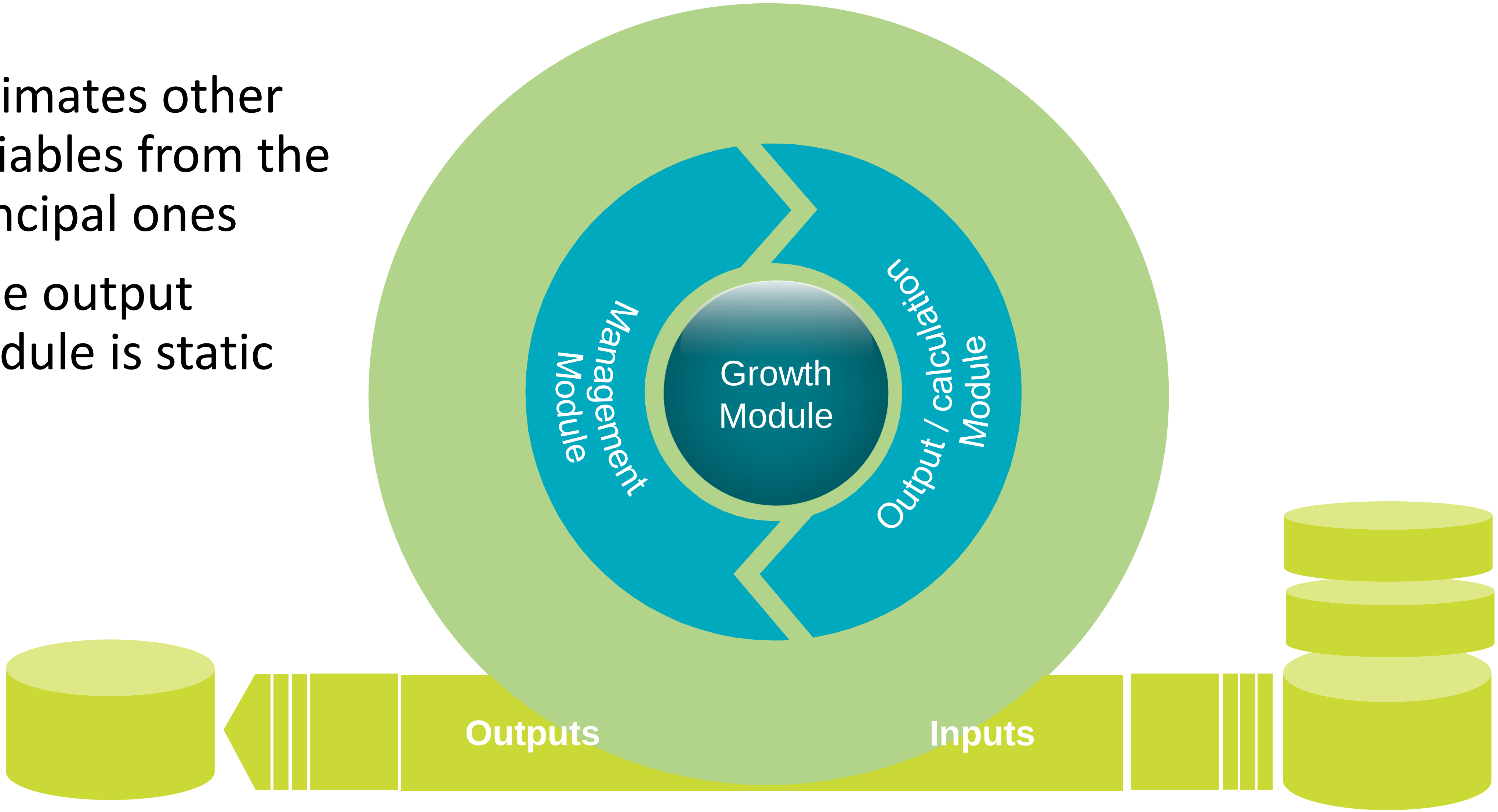
✓Controls growth by a set of silvicultural operations



# ▪Forest model

✓Estimates other variables from the principal ones

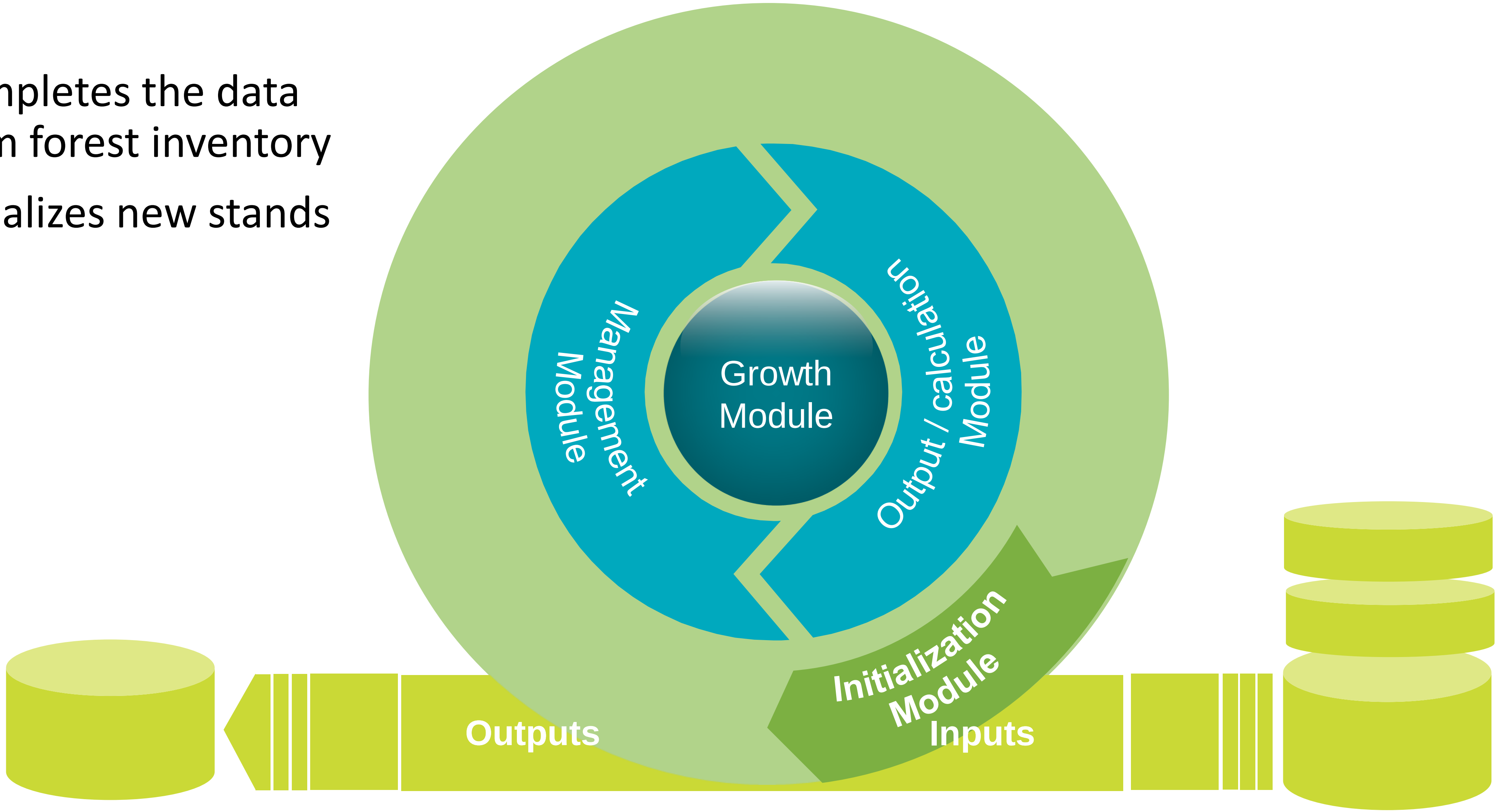
✓ The output module is static



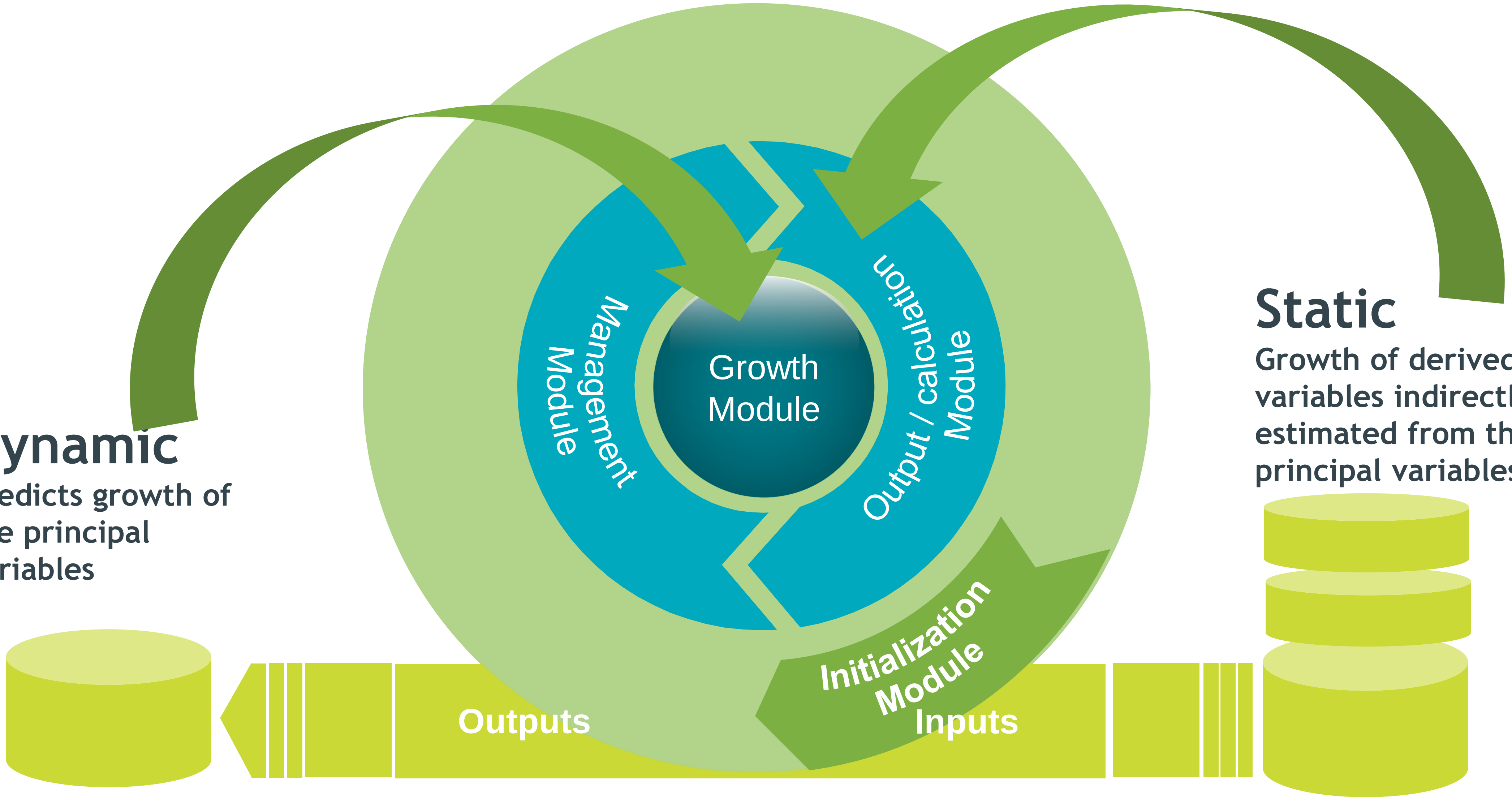
# ▪Forest model

✓Completes the data from forest inventory

✓Initializes new stands



# ▪Forest model




**Dynamic**
Predicts growth of the principal variables

**Static**
Growth of derived variables indirectly estimated from the principal variables

## ▪Driving variables (Cost Action FP0603 terminology)

- ✓ Variables that are not part of the forest model (some are part of the forest ecosystem) but influence its behaviour:
  - – **Environmental variables** (*e.g.* climate, soil)
  - – **Human induced** variables (*e.g.* silvicultural operations)
  - – **Risks** (*e.g.* fire, pests and diseases, storms)

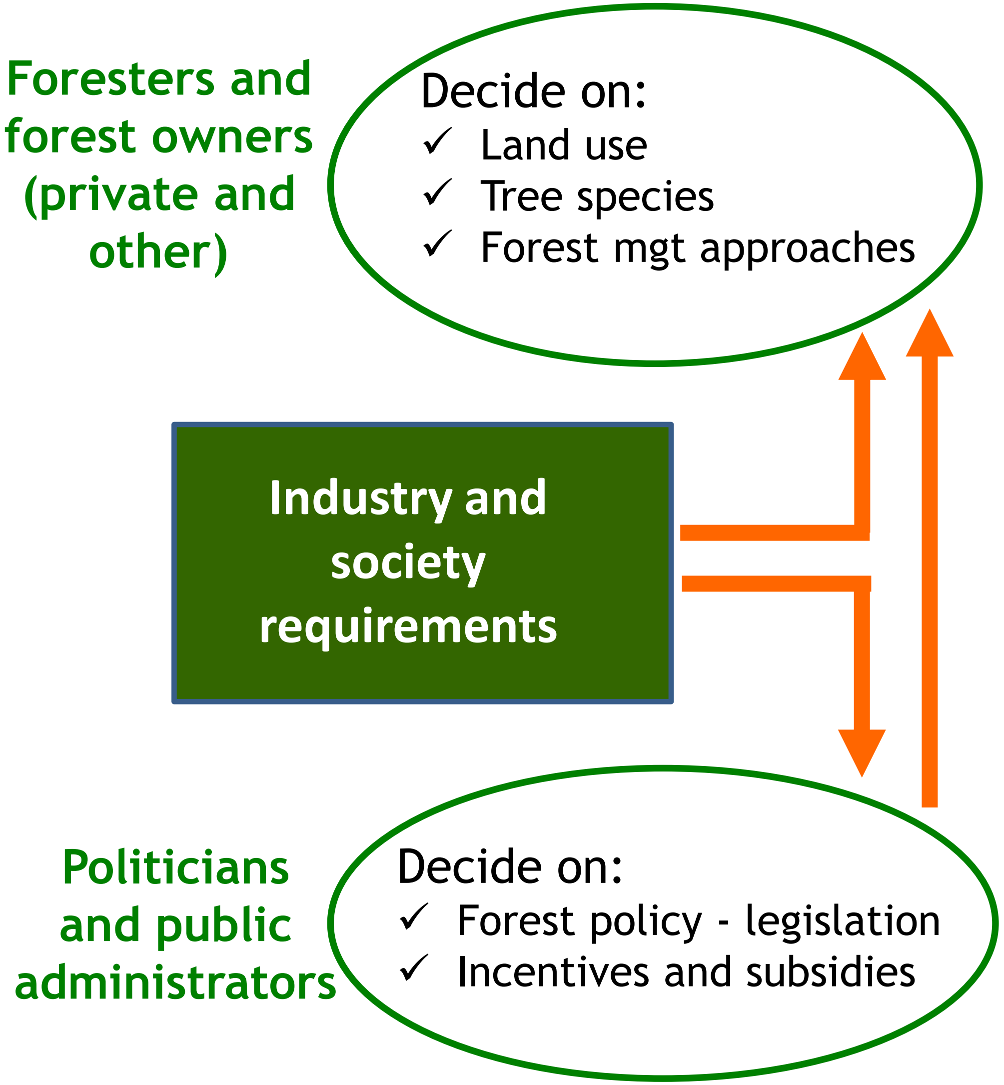
- ✓ **The separation between state and driving variables is sometimes not straighforward**

## ▪Forest simulator (Cost Action FP0603 terminology)

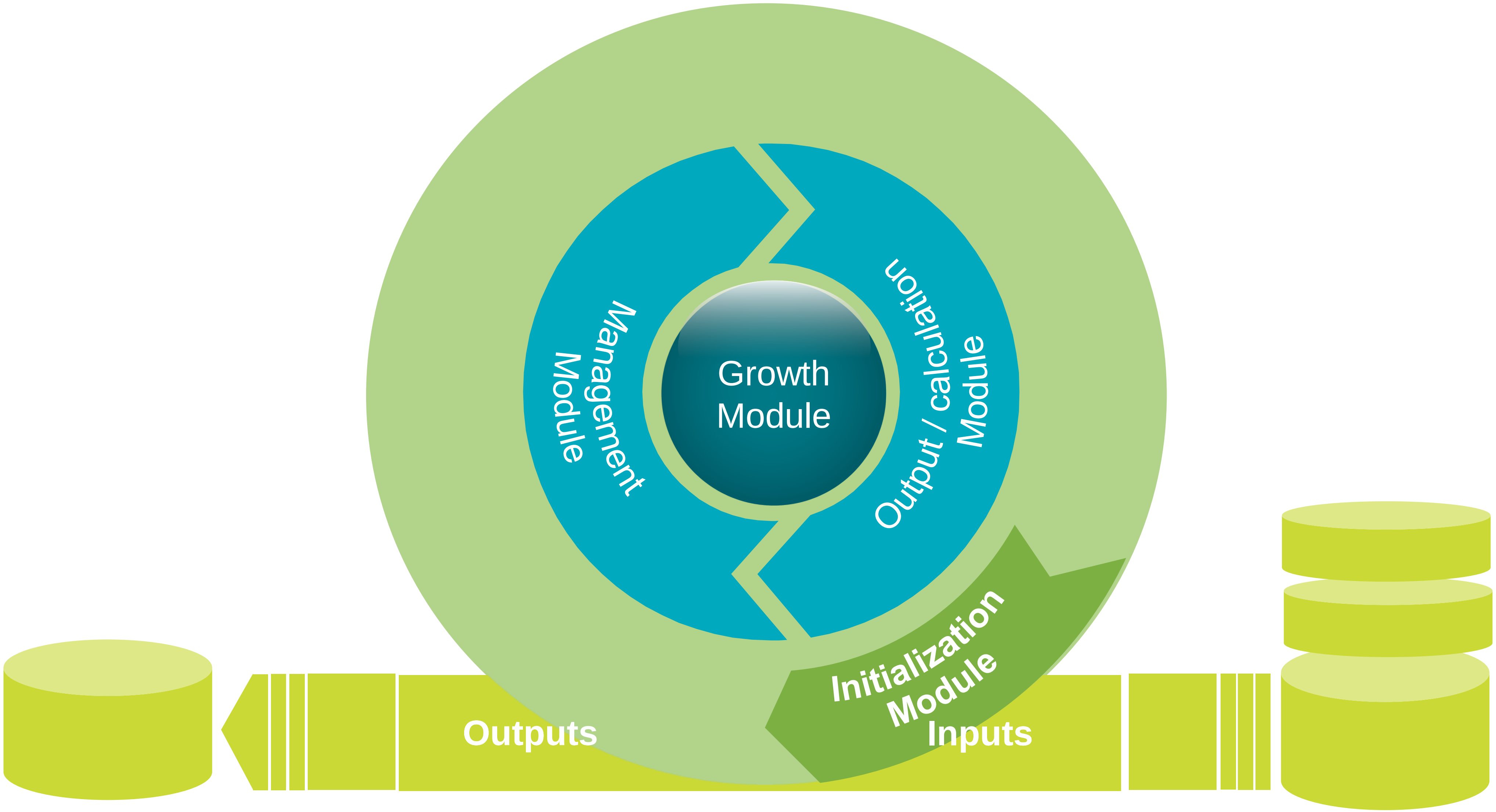
- ✓ **Computer tool** that, based on a set of forest models, makes long term predictions of the status of a forest under a certain scenario of management, climate, risks, forest policy
- ✓ Forest simulators usually predict, at each point in time, **wood and non-wood products** from the forest
- ✓ It is desirable that they predict a large range of **ecosystem services**
- ✓ They may be developed for different spatial levels

# ▪Forest management decisions at different spatial scales:

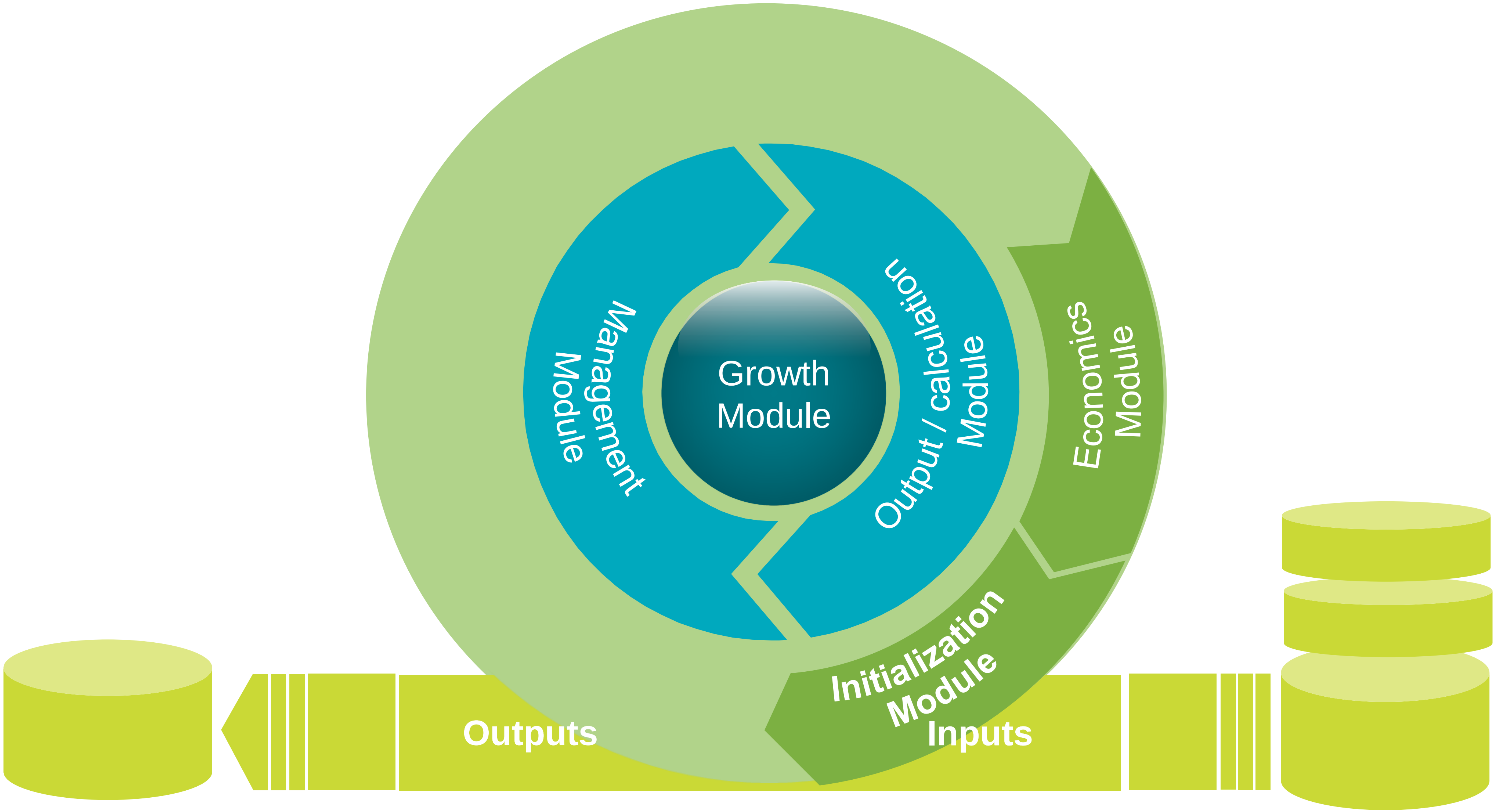
- ✓ stand
  homogeneous forest area
- ✓ management unit
  set of stands with a common management plan
- ✓ watershed, landscape
- ✓ region (e.g. PROF)
- ✓ country
- ✓ continent



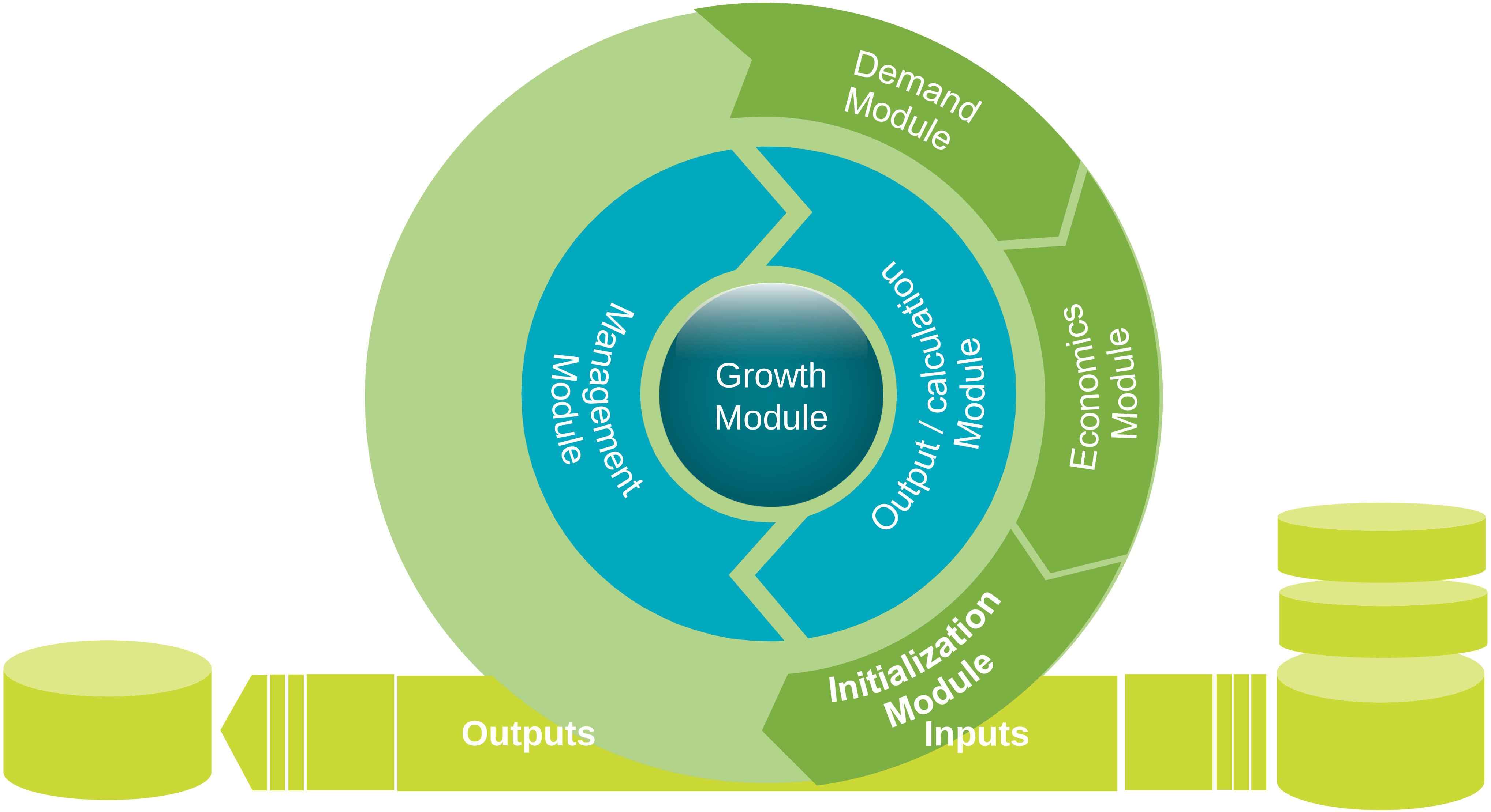
# ▪Forest model



# ▪Stand simulator



# ▪Management unit and large scale simulators



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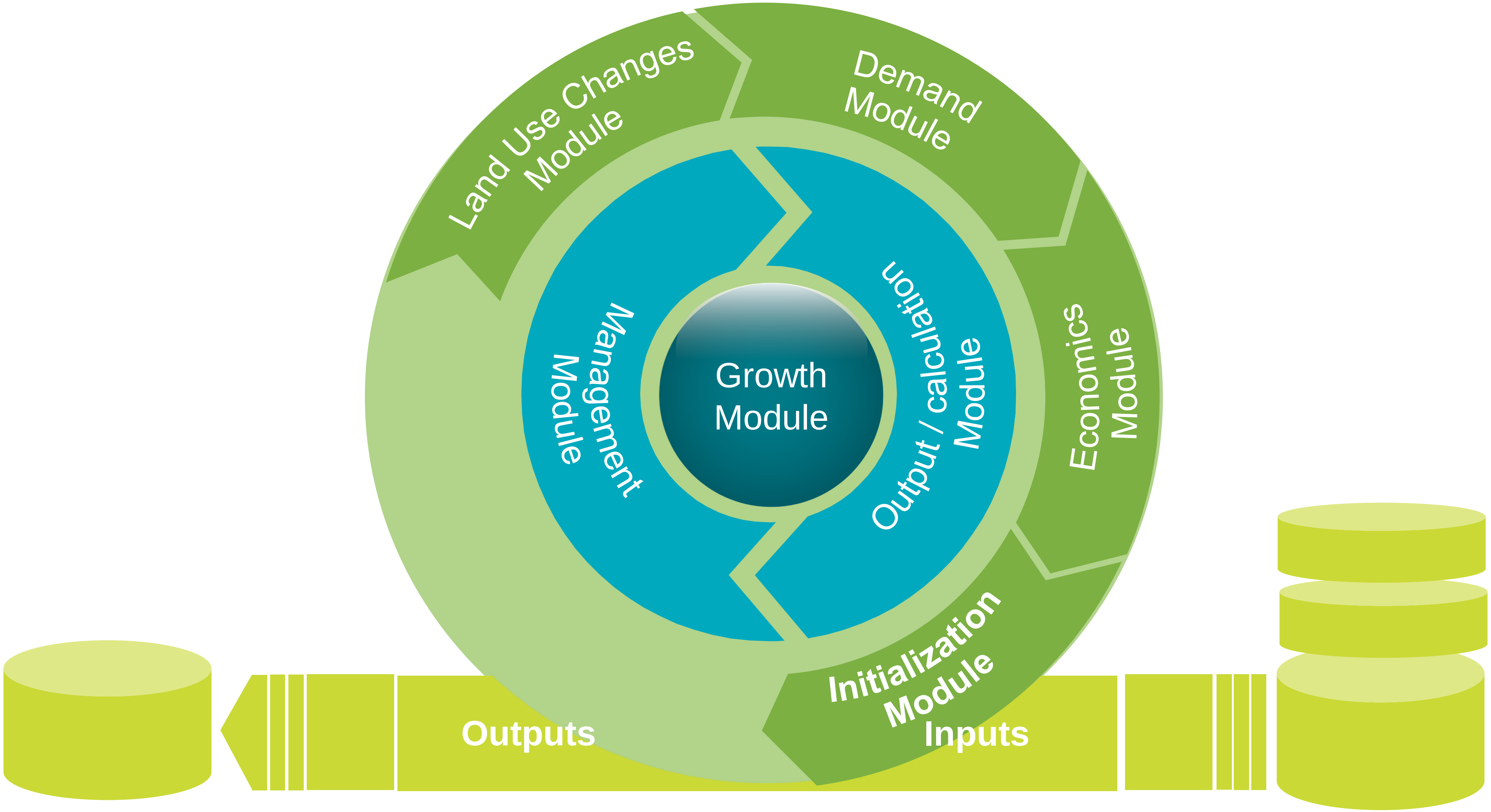
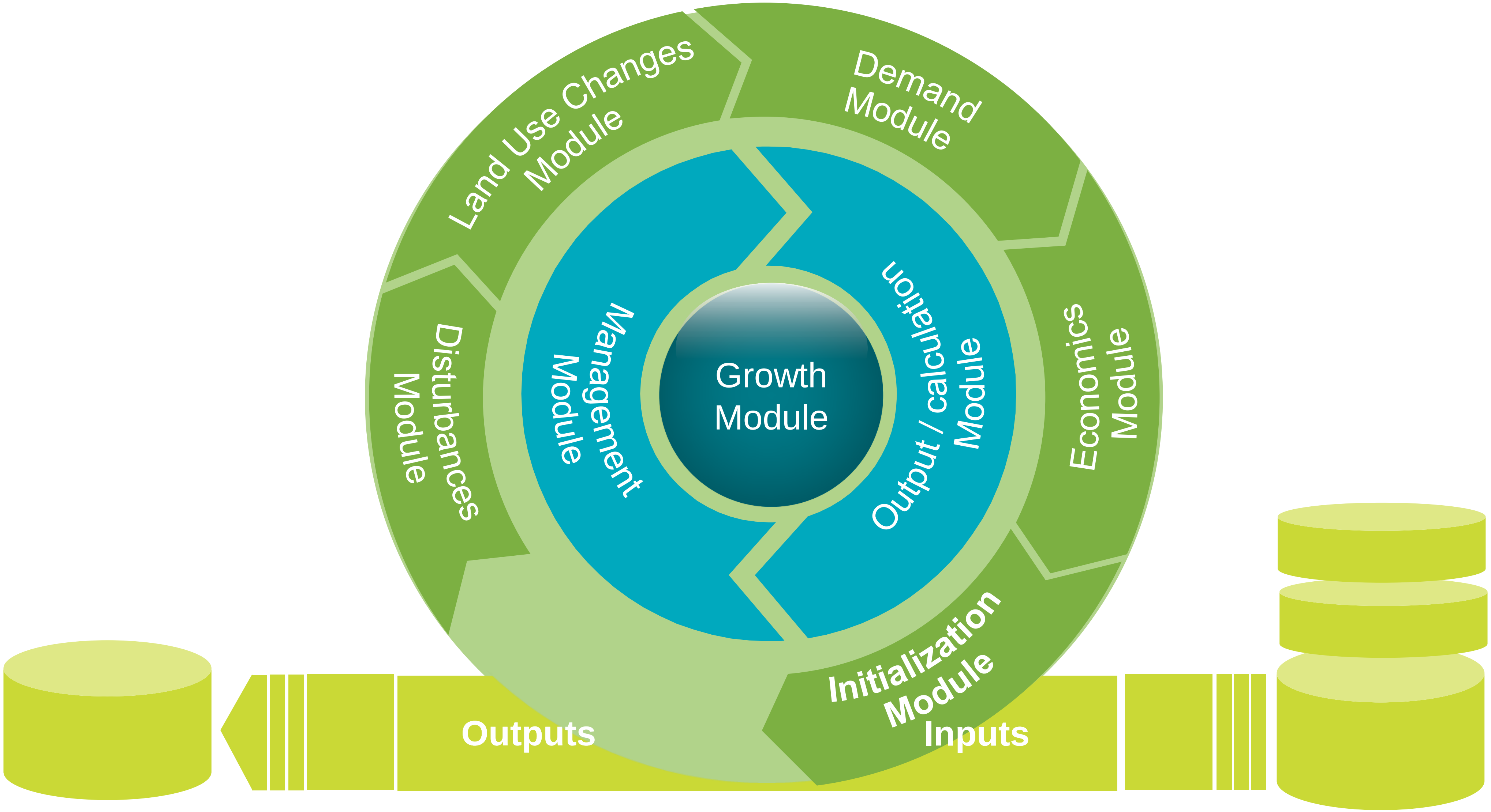
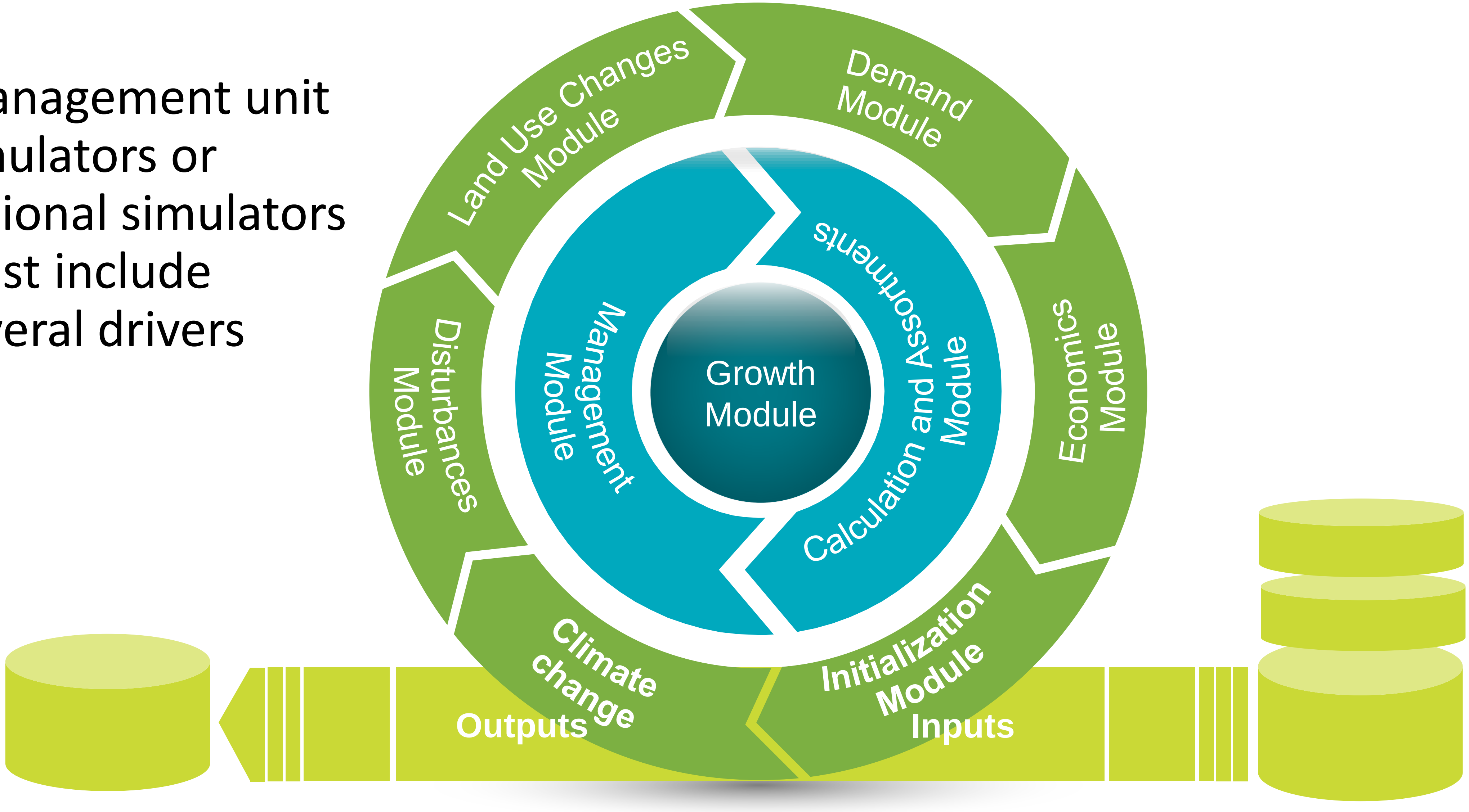


## ▪Management unit and large scale simulators



# ▪Management unit and large scale simulators

✓Management unit simulators or regional simulators must include several drivers



## Management unit (MU)

*Characterisation of each stand in the MU (values of state variables) at time t+1*

Forest inventory or/and Initialization module

*Forest simulator computer program*

*(includes a set of forest growth models)*

*Prediction of wood & non-wood products and ecosystem services*

*Forest evolution of each stand in the MU under a certain management approach (FMA)*

*Status of the forest (state variables) over time*

## Forest simulator

## ▪Decision support system (Cost Action FP0603 terminology)

✓ Simulator that includes optimization algorithms that point out for a solution – selection of a forest management approach for each stand:

- Multi-criteria decision models
- Artificial neural networks
- Knowledge based systems

*Characterisation of each stand in the MU (values of state variables) at time t*

**Forest inventory**

*Models and methods to select management options that may sustain conditions and outcomes of interest*

*(multiple criteria)*

*Forest simulator computer program*

*(includes a set of forest growth models)*

**Forest simulator applied several times to each stand**

*Simulation of several forest management alternatives (MA) for each stand*

*Prediction of wood & non-wood products and ecosystem services for each combination of FMA*

**Optimization and other OR techniques**

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} corkA_{ijt}x_{ij} = CORKA_t,\ t = 1, \ldots, T$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} cones_{ijt}x_{ij} = Cones_t,\ t = 1, \ldots, T$$

**Decision support system**

## ▪Evolution of forest growth models and respective typology

Forestry and forest management evolution

+

Increased knowledge about ecosystems functioning

+

Technology development

+

Climate change

+

- Change in society requirements from forests

↓

**EVOLUTION OF FOREST GROWTH MODELS**

# Forest growth models

**Classification according to the growth module (to be used in practice all models need a static module)**

- Empirical growth and yield models
- Semi-empirical models (LUE)
  - 3PG
  - YieldSAFE
  - ---
- Process based models

# ▪Statistical FGMs (empirical G&Y)

- ✓ Developed using statistical techniques and calibrated for large data-sets
- ✓ The site index (hdom at a given base-age) is often used as a proxy for environmental conditions
- ✓ Growth is usually modeled with the so-called growth functions
- ✓ Adequately describe growth for a range of silvicultural practices and site conditions
- ✓ Some are able to predict wood quality properties
- ✓ Exist for all of the most important forest types in Europe and most of them have been extensively validated
- ✓ Do not allow for the simulation of forest growth under a changing environment or subject to novel silvicultural practices

# The G&Y model GLOBULUS (empirical)

**Table 1.** Site Index and dominant height projection functions.

**Site Index and Dominant height**

(1) SI = ...

| model |
|---|
| (1) and (2) |

Where SI is the si...
(tp=10 for eucalypt...
2 represent the ins...

**Table 2.** Basal area: initialization function (1) and growth projection function (2).

**Basal Area**

$$(1)\ G = A_G\ e^{-k_G \left(\frac{1}{t}\right)^{(n_{Gp} + \dots}}$$

$$A_G = (a_{G0} + a_{G1}\ DR)$$

$$n_{Gp} = n_{G0} + \frac{n_{G1}}{\left(1 - \left(\frac{cota}{2000}\right.\right.}$$

| model | $a_{G0}$ | $a_{G1}$ | $k_{G0}$ |
|---|---|---|---|
| (1) | 80.1683 | 0.2354 | 8.8294 |
| (2) | 80.1683 | 0.2354 | - |

Where G is the stand basal area; t ...
Symbols); SI is the site index; Cota ...
stand rotation (0 for planted and 1 f...
time.

**Table 3.** Functions to predict the evolution of the number of trees, stumps and shoots

**Density and/or Mortality**

Planted Stands:

$$(1)\ N = Npl\ e^{-am\ t}$$

$$(2)\ N_2 = N_1\ e^{-am\ (t_2 - t_1)}$$

Coppice Stands:

$$(3)\ N_{stools} = N_{harv}\ (1 - dea\dots$$

$$(4)\ N_{stools\ 2} = N_{stools\ 1}\ e^{-a\dots}$$

$$(5)\ N_{sprouts\ t \le 2} = N_{stools}\ \dots$$

$$(6)\ N_{sprouts\ t=3} = \frac{\dots}{1 - e^{-\left(am\dots\right.}}$$

If there is any kind of sprouts selecti...
=1.6

**Table 4.** Volume initialization function (1) and Volume projection function (2),

**Volume Total**

$$(1)\ V_i = Kv\ t^{a}\ hdo\dots$$

$$(2)\ V_{i2} = V_{i1} \left(\frac{t_2}{t_1}\right)^{a} \left(\frac{h\dots}{h\dots}\right.$$

| model | a |
|---|---|
| (1) Vu | -0.0510 |
| (2) Vu | -0.0511 |
| (1) Vb | -0.0548 |
| (2) Vb | -0.0548 |
| (1) V_st | -0.0821 |
| (2) V_st | -0.0821 |

Where Vi represents the ...

**Table 6.** Biomass prediction functions

**Biomass**

$$W_i = a\ G^{b}\ hdom^{c} \qquad b = b_0 + b_1\ rot + b_2 \left(\frac{N}{1000}\right) + b_3 \left(\frac{SI}{1000}\right) + b_4 \left(\frac{t}{1000}\right)$$

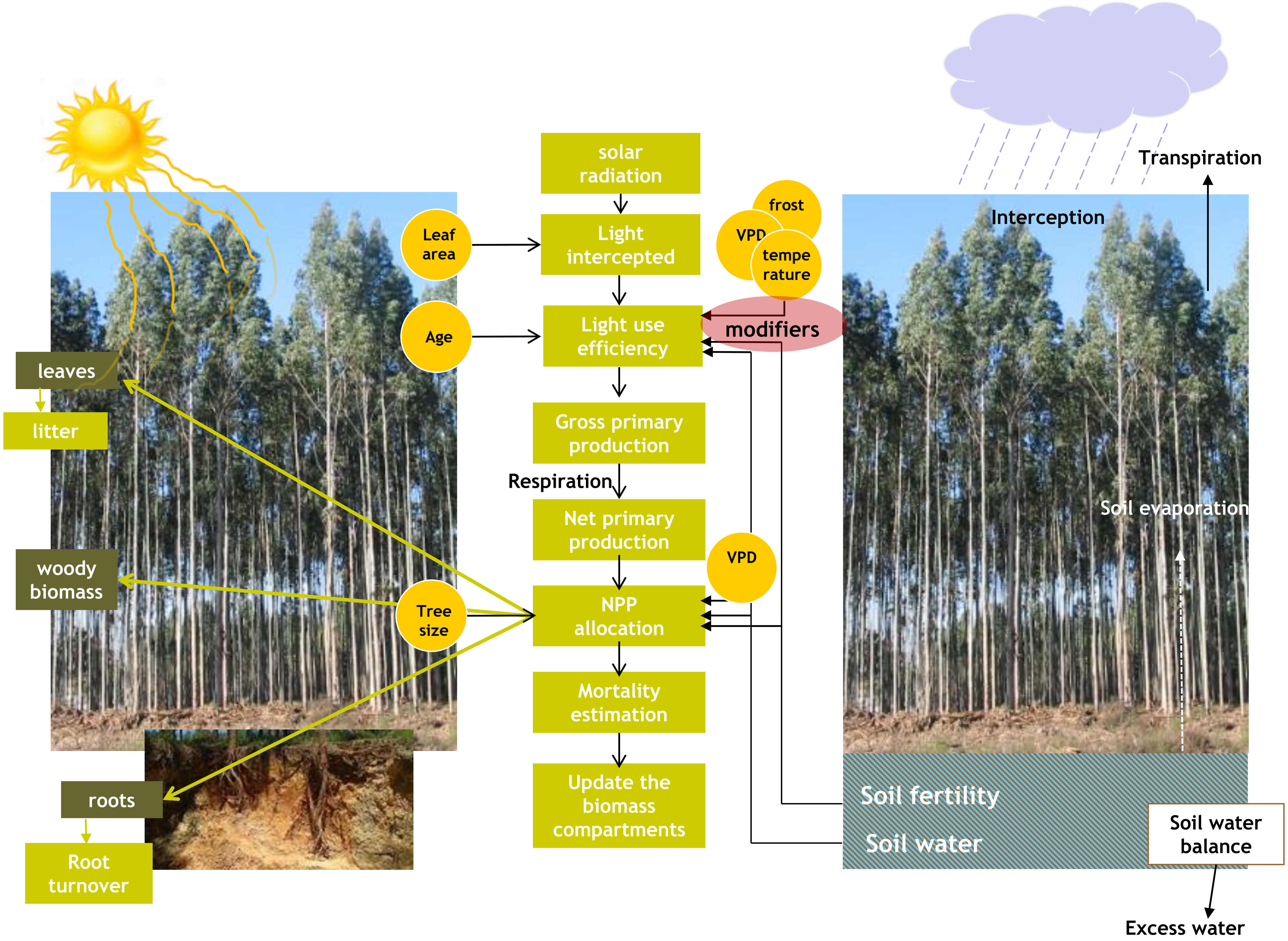
$$W_a = W_w + W_b + W_l + W_{br} \qquad W_r = a\ W_a \qquad W_t = W_a + W_r$$

| model | a | b₀ | b₁ | b₂ | b₃ | b₄ | c |
|---|---|---|---|---|---|---|---|
| $W_w$ | 0.0967 | 1.0547 | -0.0018 | -0.0065 | -0.5198 | -1.2105 | 1.1886 |
| $W_b$ | 0.03636 | 1.1691 | -0.0083 | -0.0459 | 3.2289 | 2.0880 | 0.6710 |
| $W_l$ | 1.0440 | 1.0971 | - | -0.0112 | -1.2207 | -6.2807 | -0.3129 |
| $W_{br}$ | 0.3972 | 1.0005 | - | -0.0192 | 3.3170 | -1.2747 | -0.0160 |
| $W_r$ | 0.2487 | - | - | - | - | - | - |

Where Wi represents the following biomass components: Ww is the biomass of wood, Wb is the biomass of bark, Wbr is the biomass of branches and Wl is the biomass of leaves; Wa is the ttotal aboveground biomass; Wr is the biomass of roots;hdom is the stand dominant height; G is the stand basal area; SI is the site index; rot is the stand rotation (0 for planted and 1 for coppice stands); N is the stand density and

# Process-based ecophysiological models

- Developed to understand forest behavior from a description of plant-soil and carbon-nutrient-water interactions
- Allow the simulation of forest growth under a changing environment or subject to novel silvicultural practices
- The principal variables are biomass pools per tree component (leaves, branches, roots, wood)
- A specific problem with this type of model is the need for detailed input, demanding data which are rarely available at regional or lower levels
- Do not give all the output needed for forest management (but it can be easily added)



solar radiation
Light intercepted
Light use efficiency
Gross primary production
Respiration
Net primary production
NPP allocation
Mortality estimation
Update the biomass compartments
Leaf area
Age
Tree size
frost
VPD
tempe rature
modifiers
VPD
leaves
litter
woody biomass
roots
Root turnover
Transpiration
Interception
Soil evaporation
Soil fertility
Soil water
Soil water balance
Excess water

# Growth modifiers in 3PG

- Each environmental factor is represented by a growth modifier or function of the factor that varies between 0 (total limitation) and 1 (no limitation)

| **Factor** | **Modifier** | **Parameters** |
|---|---|---|
| Vapor pressure deficit | $f_{VPD}(D)$ | $k_D$ |
| Soil water | $f_{SW}(\theta)$ | $\theta_{max}, c_\theta, n_\theta$ |
| Temperature | $f_T(T_{av})$ | $T_{min}, T_{opt}, T_{max}$ |
| Frost | $f_F(d_f)$ | $k_F$ |
| Site nutrition | $f_N(FR)$ | $f_{N0}$ |
| Stand age | $f_{age}(t)$ | $n_{age}, r_{age}$ |

# An example: temperature growth modifier $f_T(T)$

$$f_T(T) = \left( \frac{T - T_{min}}{T_{opt} - T_{min}} \right) \left( \frac{T_{max} - T}{T_{max} - T_{opt}} \right)^{(T_{max} - T_{opt})/(T_{opt} - T_{min})}$$

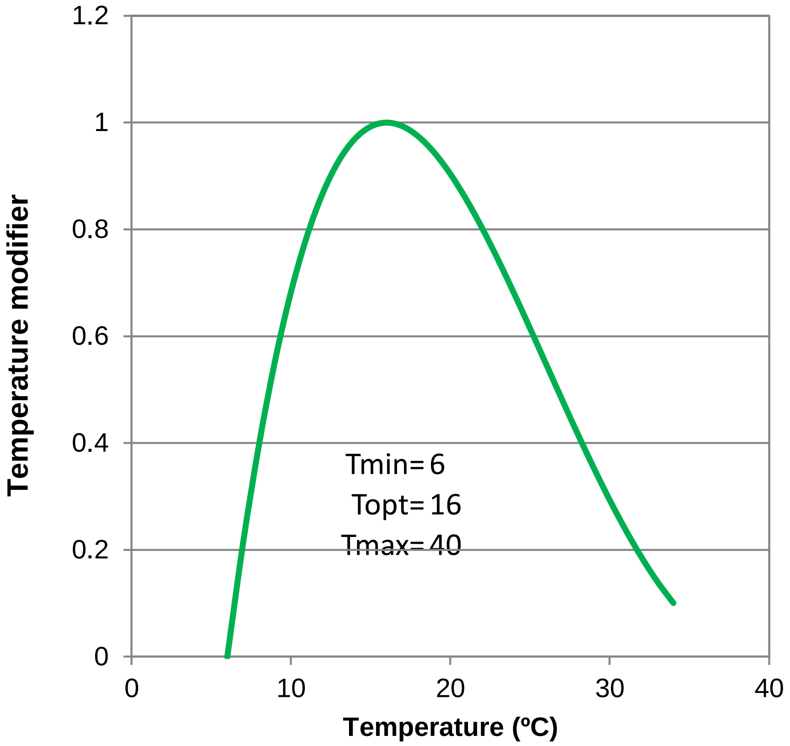
where

$T$ = mean monthly daily temperature

$T_{min}$ = minimum temperature for growth

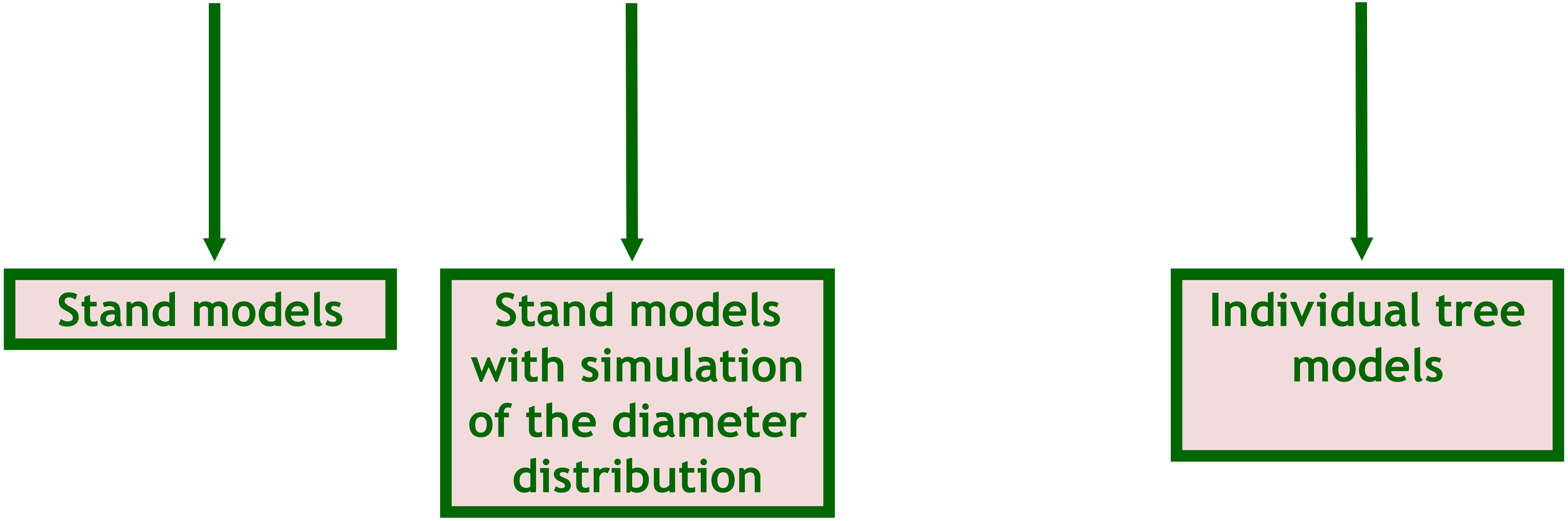
$T_{opt}$ = optimum temperature for growth

$T_{max}$ = maximum temperature for growth



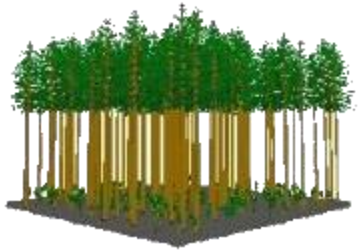
# Forest growth models

## Classification according to the unit of simulation (growth module)

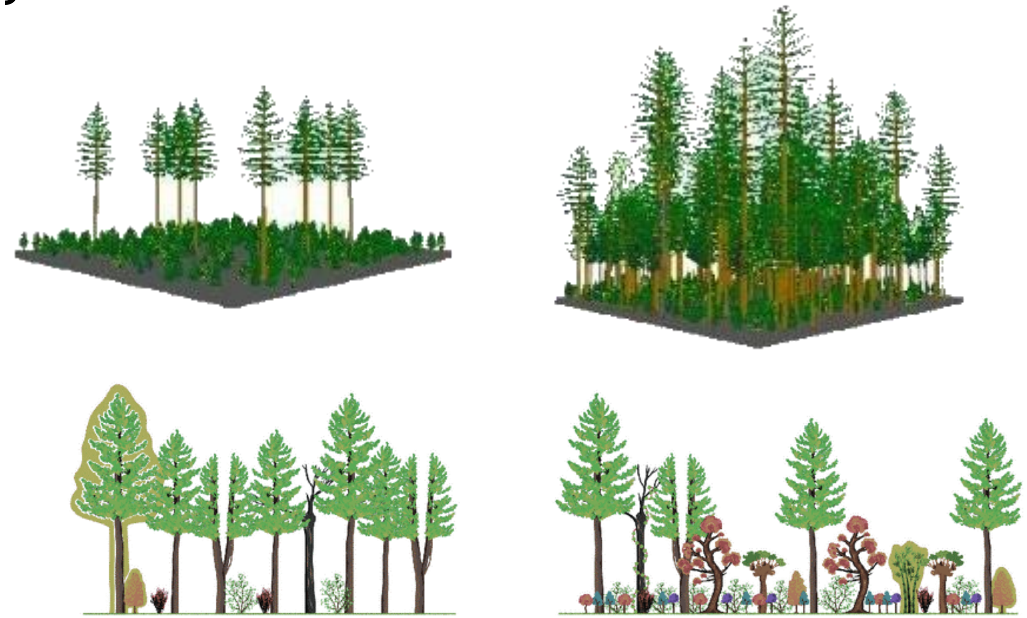


# ▪Stand model *versus* individual tree model

- ✓ All principal variables are **stand variables**
- ✓ Inter-tree competition is expressed through **stand level competition measures**



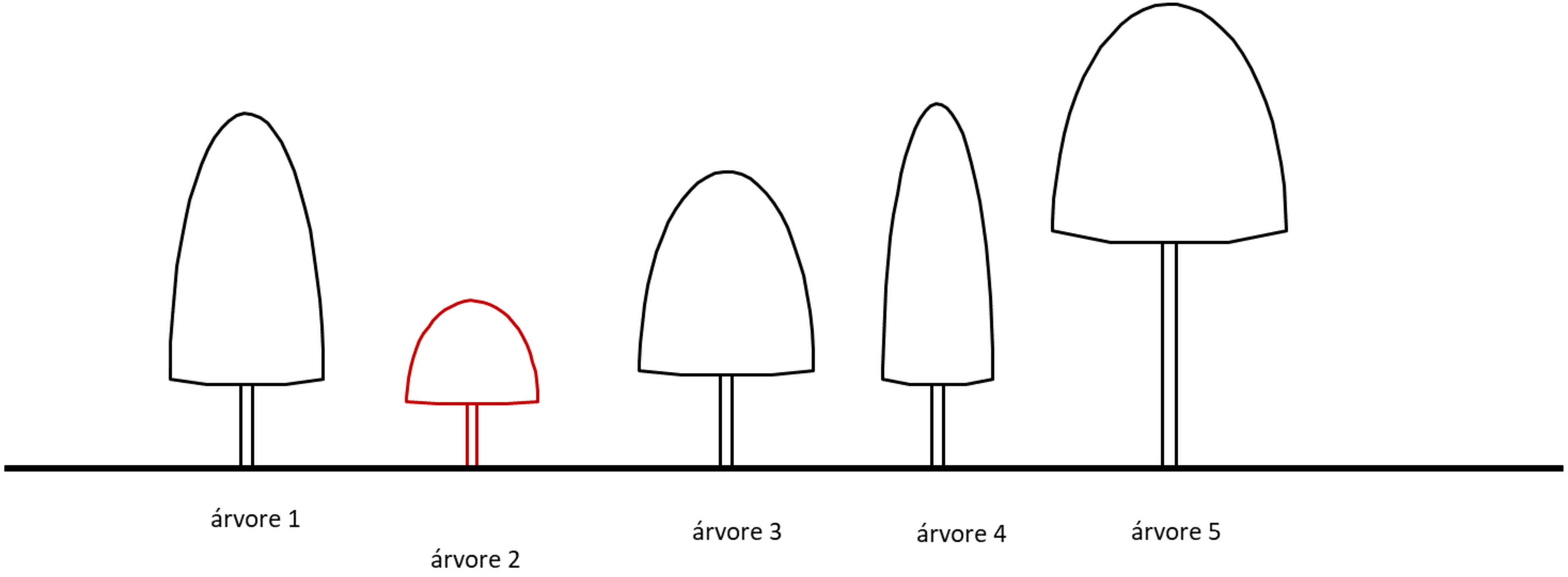
- ✓ All principal variables are **tree variables** (except hdom)
- ✓ Inter-tree competition is expressed through **competition indices** and/or light interception modules
- ✓ They are able of **simulating more complex structures** (irregular, mixed) and have much **more extrapolation** capacity



# ▪Is it important to use competition indices?

- ✓ Competition indices can be **spatially explicit** (the relative position of the trees is known) or not. In the latter, competition is evaluated by the **hierarchical position of the tree** in the stand
- ✓ The simulation of a **wide variety of thinning types** requires spatial information
- ✓ They are also required for the evaluation of alternatives regarding **silvicultural systems** and management options in **forests with a complex structure**

## ▪ Do we need spatially explicit competition indices?



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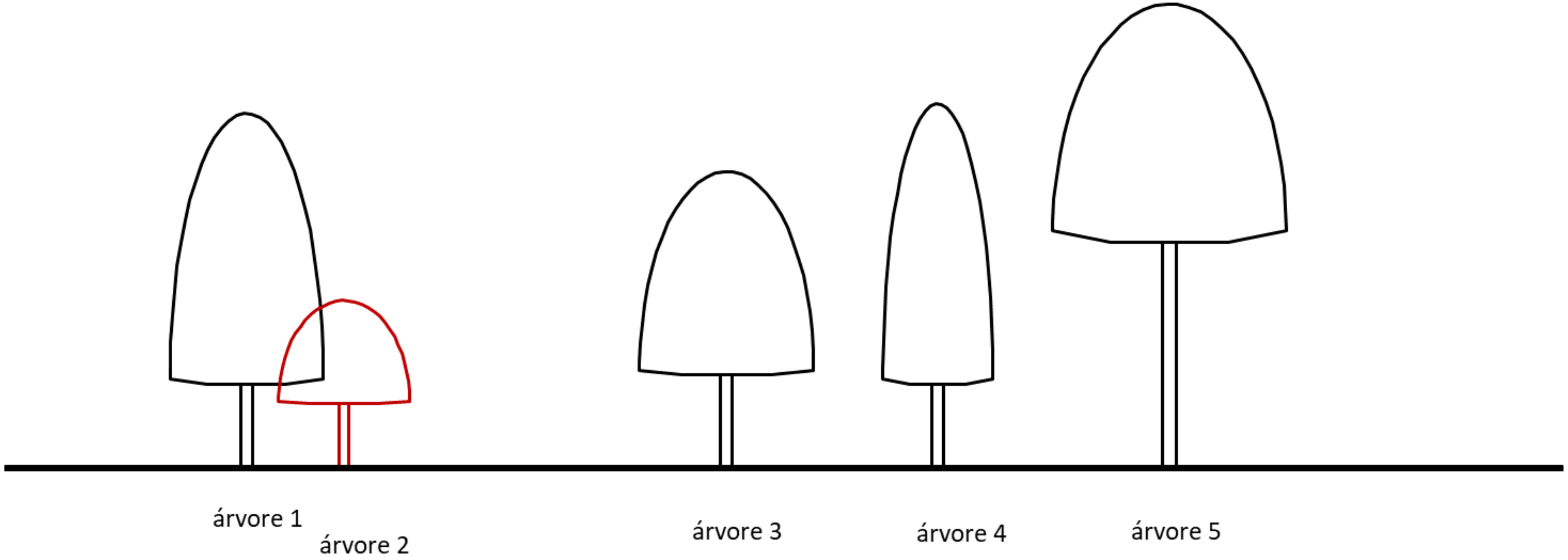

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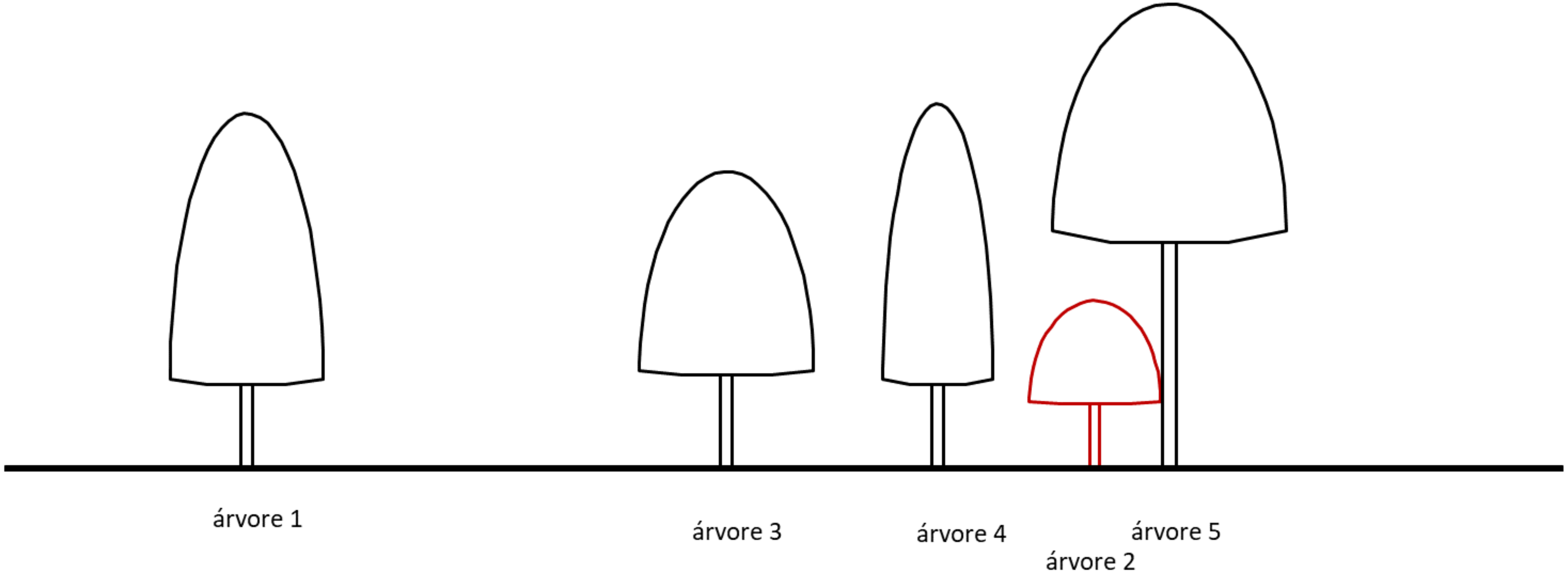
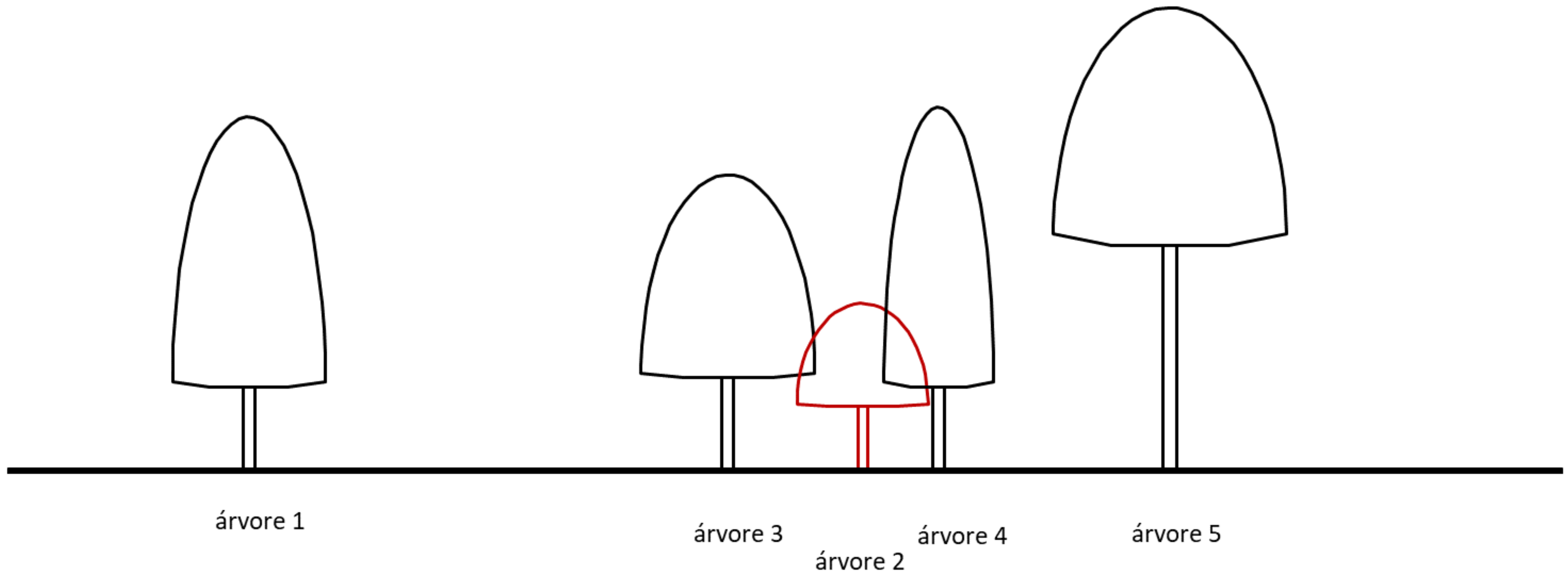
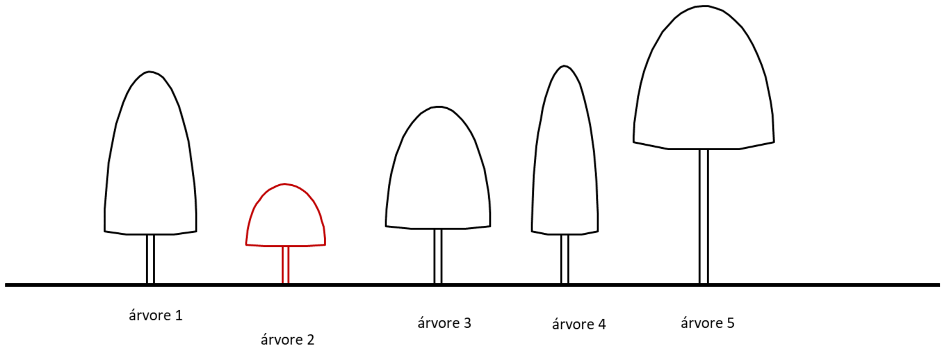


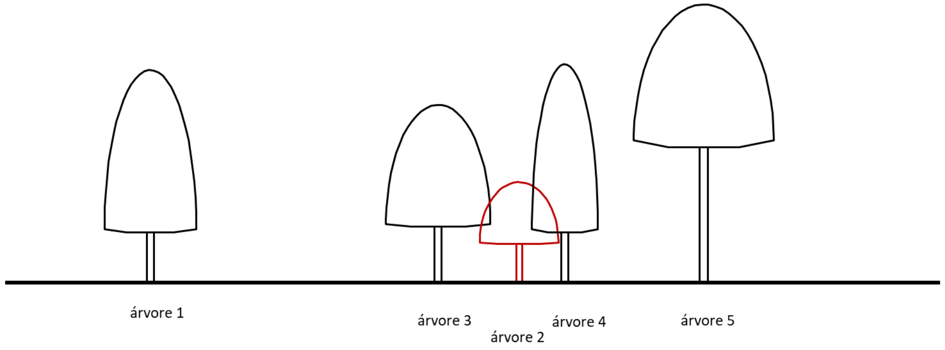
## ▪ Do we need spatially explicit competition indices?



# Do we need spatially explicit competition indices?




The **probability** that tree 2 will be selected in a thinning **is low**




The **probability** that tree 2 will be selected in a thinning **is high**

- In a thinning algorithm based on **non-spatially explicit indices**, the **probability** that tree 2 is cut **is the same** in both situations

# ▪Current forest models and sustainable forest management needs

## ▪Requirements from forest models - moving

| FROM | TO |
|---|---|
| ✓ Stand models | ✓ Individual tree models |
| ✓ Empirical models | ✓ Process based models |
| ✓ Stand simulators | ✓ Management unit simulators |
| ✓ Simple structure forests | ✓ Complex forests (uneven and mixed) |
| ✓ Focusing just trees | ✓ Focusing other ecosystem components (e.g shrubs, soils) |
| ✓ Simple output, mainly traditional stand variables and volume harvested | ✓ Diversified outpus, including social, economic and ecological indicators, including ecosystem services |

**Life is not easy for growth modelers!!**

# ▪Present models need improvement

✓ There is the need for **more detailed, versatile forest growth models** that

- can work using readily available forest inventory data as input
- are able to give good predictions under climate change
- take into account the genetics of the plant material
- provide information on the effect of different silvicultural alternatives not only on tree growth but also on other forest products and services (indicators of MSFM)
- provide reliable information on stand structure and wood quality
- account for the possible occurrence of several damages

# ▪Present models need improvement

- ✓ Current models:
  - – Do not include risk assessment such as storm damage, fire, pests and diseases
  - – Concentrate output on the development of trees (do not give output on the impact of forests and forest management on soils and water use, biodiversity, recreational and amenity values, etc)
  - – Do not simulate wood quality
  - – Do not simulate the impact of genetic improvement
- ✓ There are models covering some of these aspects but generally these aspects are not covered

# Present models need improvement

- Scientifically there is the need to **improve the knowledge of the forest ecosystems** to be able to predict stand growth and forest development under changing environmental and managerial conditions
- For forestry practice
  - there is the need to improve output quality regarding the level of detail as well as the accuracy of predictions
  - for instance good information on stand structure is essential to assess wood quality or to evaluate harvesting procedures and costs

## ▪The need to use landscape forest simulators

- ✓ For instance modelling fire impacts includes several steps
  - – Predicting the probability of occurrence
  - – Once it occurs, predict the “propagation of the risk”
  - – Predict the impact (tree death, decrease in productivity, etc)
- ✓ It can only be done at landscape/larger spatial scales and requires that the model includes new variables (such as height of shrubs, shrub biomass, height to the base of the crown, crown bulk density)

**The integration of models into management unit / large scale forest simulators is a requirement of modern forest management**

# ▪Stages in model development

# Stages in model development

- Data collection

  → Model quality depends, to a great extent, on data quality

# Stages in model development

- Selection of model type
  - ➔ Stand model
    - Without simulation of diameter distributions
    - With simulation of diameter distribution
  - ➔ Individual tree model
    - Distance dependent
    - Distance independent
  - ➔ Process based model
  - ➔ Hybrid model

# Stages in model development

- Design of the structure of the model (the “true” building of the model)
  - ➔ Selection of external variables, both cultural (e.g. planting density, silviculture alternatives) and environmental (e.g. site index, precipitation)
  - ➔ Selection os state variables, both principal and secondary (model components)
  - ➔ Establishment of the relationhsips among the variables
  - ➔ Selection of the functions to model each model component, both growth functions, for principal variables, and prediction equations, for derived variables

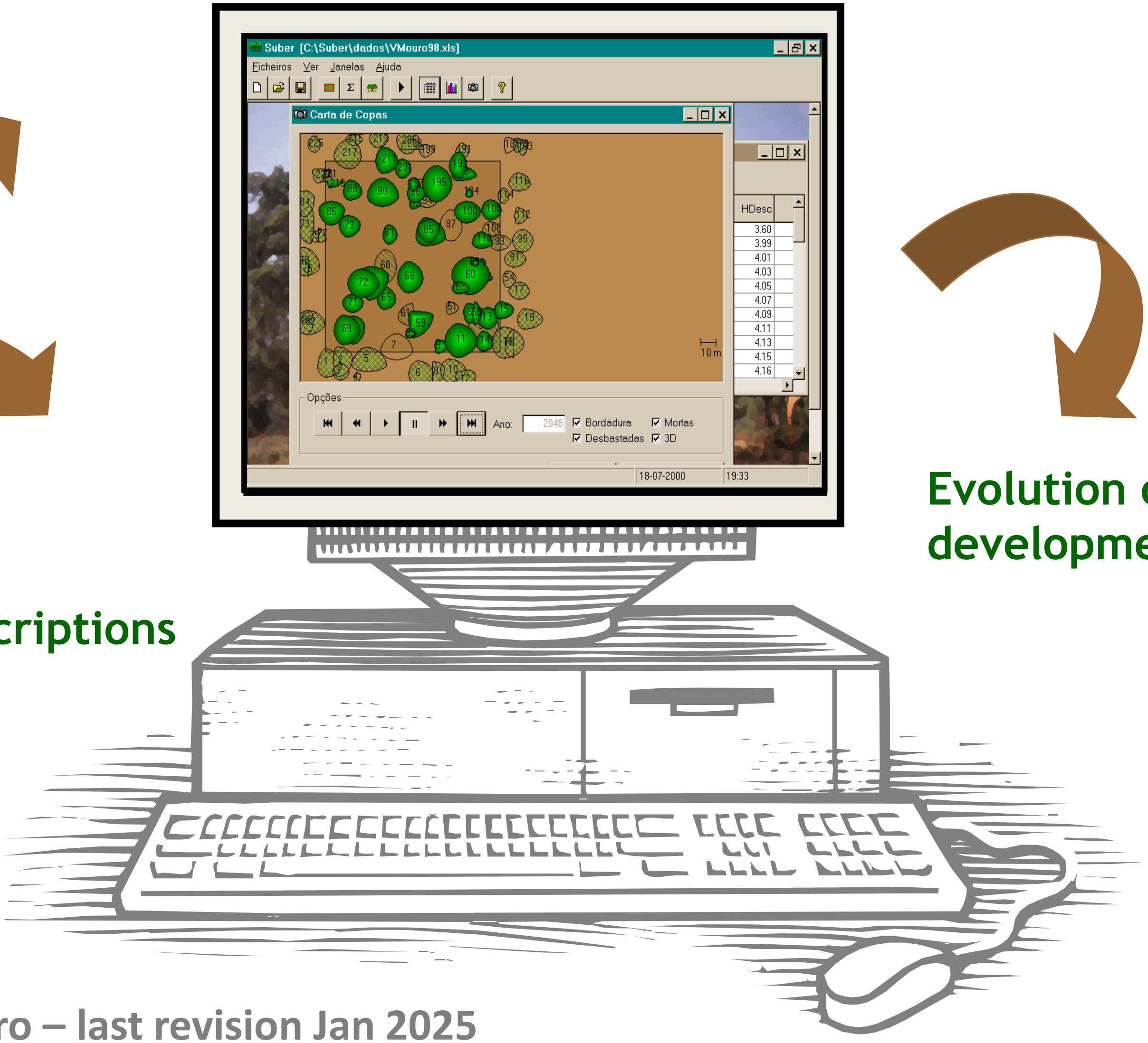
# Stages in model development

- Model evaluation
  - ➔ Analysis of the behaviour of the model according to existing theories (growth and yield theory as well as ecological theories)
  - ➔ Comparing the simulations of the model with real growth data (independent from those used to develop the model)
- Implementation of the model into a computer program and/or a decision support system (forest simulador)
  - ➔ Essential for the operational use of the model

# ▪Forest simulators at different spatial scales

- Stand simulators

Stand characteristics



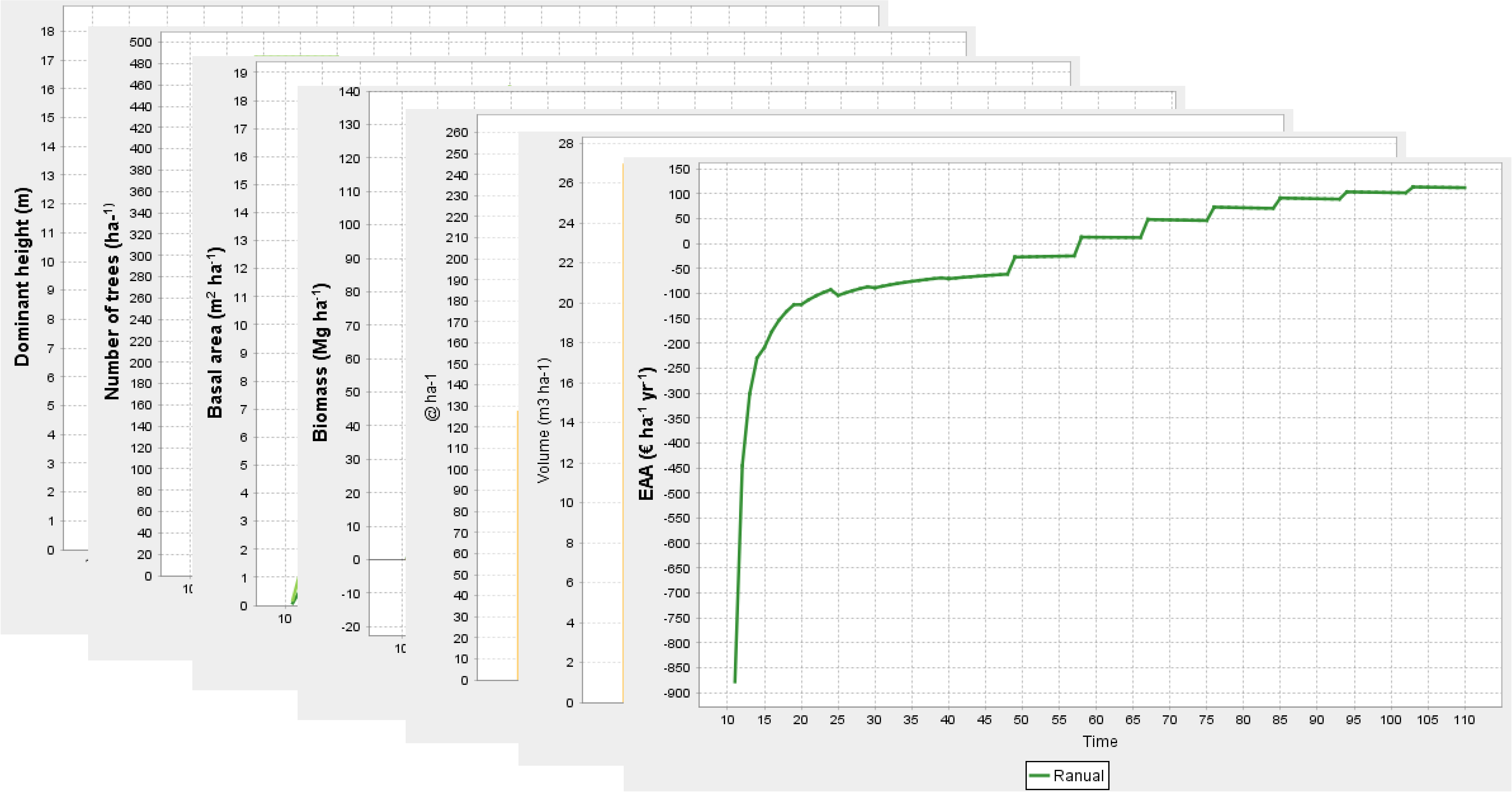

Evolution of stand development

FMAs and prescriptions
Scenarios

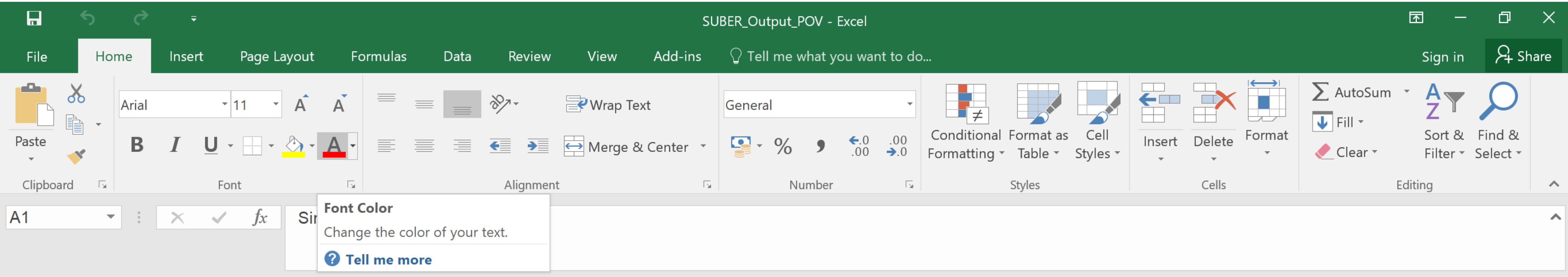
# Example with the SUBER model

- 11 years old plantation in Portugal (Chamusca)
- A forest inventory took place

# Example with the SUBER model



# Example with the SUBER model

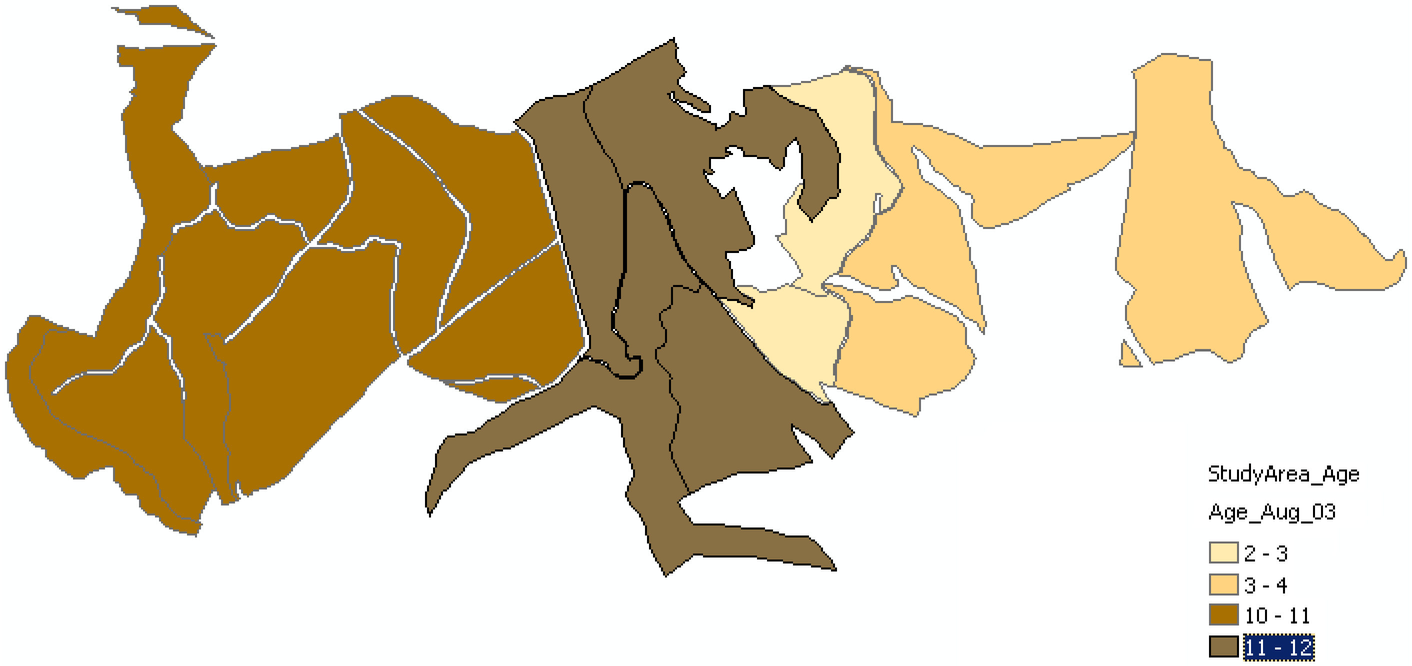



| Simulation | 100 | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| year | t | idesc | idesb | N | N7_5 | Nreg | Nmor | Ndesb | G | Gu | hdom | V | V75 | Ww | Wb | Wc | W |
| 2016 | 1 | 0 | 0 | 0 | 0 | 417 | 0 | 0 | 0 | 0 | 0.09 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2017 | 2 | 0 | 0 | 0 | 0 | 407 | 0 | 0 | 0 | 0 | 0.26 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2018 | 3 | 0 | 0 | 0 | 0 | 399 | 0 | 0 | 0 | 0 | 0.46 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2019 | 4 | 0 | 0 | 0 | 0 | 392 | 0 | 0 | 0 | 0 | 0.69 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2020 | 5 | 0 | 0 | 0 | 0 | 386 | 0 | 0 | 0 | 0 | 0.93 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2021 | 6 | 0 | 0 | 0 | 0 | 377 | 0 | 0 | 0 | 0 | 1.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2022 | 7 | 0 | 0 | 0 | 0 | 372 | 0 | 0 | 0 | 0 | 1.48 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2023 | 8 | 0 | 0 | 164 | 0 | 199 | 2 | 0 | 0.57 | 0.21 | 1.77 | 0.38 | 1.28 | 0.1 | 0.96 | 1.43 | 2.49 |
| 2024 | 9 | 0 | 0 | 340 | 164 | 16 | 9 | 0 | 1.5 | 0.59 | 2.06 | 1.09 | 3.63 | 0.34 | 2.44 | 3.63 | 6.41 |
| 2025 | 10 | 0 | 0 | 349 | 335 | 0 | 16 | 0 | 1.88 | 0.79 | 2.37 | 1.49 | 4.88 | 0.51 | 2.98 | 4.43 | 7.92 |
| 2026 | 11 | 0 | 0 | 346 | 346 | 0 | 19 | 0 | 2.23 | 0.98 | 2.67 | 1.88 | 6.09 | 0.71 | 3.42 | 5.09 | 9.22 |
| 2027 | 12 | 0 | 0 | 342 | 342 | 0 | 23 | 0 | 2.6 | 1.19 | 2.98 | 2.31 | 7.4 | 0.95 | 3.86 | 5.75 | 10.55 |
| 2028 | 13 | 0 | 0 | 342 | 342 | 0 | 23 | 0 | 3.02 | 1.43 | 3.29 | 2.81 | 8.89 | 1.25 | 4.34 | 6.47 | 12.05 |
| 2029 | 14 | 0 | 0 | 340 | 340 | 0 | 25 | 0 | 3.44 | 1.68 | 3.6 | 3.33 | 10.45 | 1.58 | 4.8 | 7.16 | 13.54 |
| 2030 | 15 | 0 | 0 | 338 | 338 | 0 | 27 | 0 | 3.88 | 1.93 | 3.9 | 3.89 | 12.09 | 1.97 | 5.26 | 7.84 | 15.07 |
| 2031 | 16 | 0 | 0 | 334 | 334 | 0 | 31 | 0 | 4.31 | 2.19 | 4.21 | 4.46 | 13.74 | 2.39 | 5.68 | 8.48 | 16.54 |
| 2032 | 17 | 0 | 0 | 330 | 330 | 0 | 35 | 0 | 4.76 | 2.47 | 4.51 | 5.06 | 15.47 | 2.86 | 6.1 | 9.11 | 18.07 |
| 2033 | 18 | 0 | 0 | 324 | 324 | 0 | 41 | 0 | 5.17 | 2.72 | 4.81 | 5.63 | 17.11 | 3.34 | 6.46 | 9.65 | 19.45 |
| 2034 | 19 | 0 | 0 | 322 | 322 | 0 | 43 | 0 | 5.66 | 3.02 | 5.1 | 6.31 | 19.03 | 3.92 | 6.9 | 10.31 | 21.13 |
| 2035 | 20 | 0 | 0 | 320 | 320 | 0 | 45 | 0 | 6.16 | 3.33 | 5.39 | 7 | 21 | 4.54 | 7.33 | 10.96 | 22.83 |

- Landscape simulator

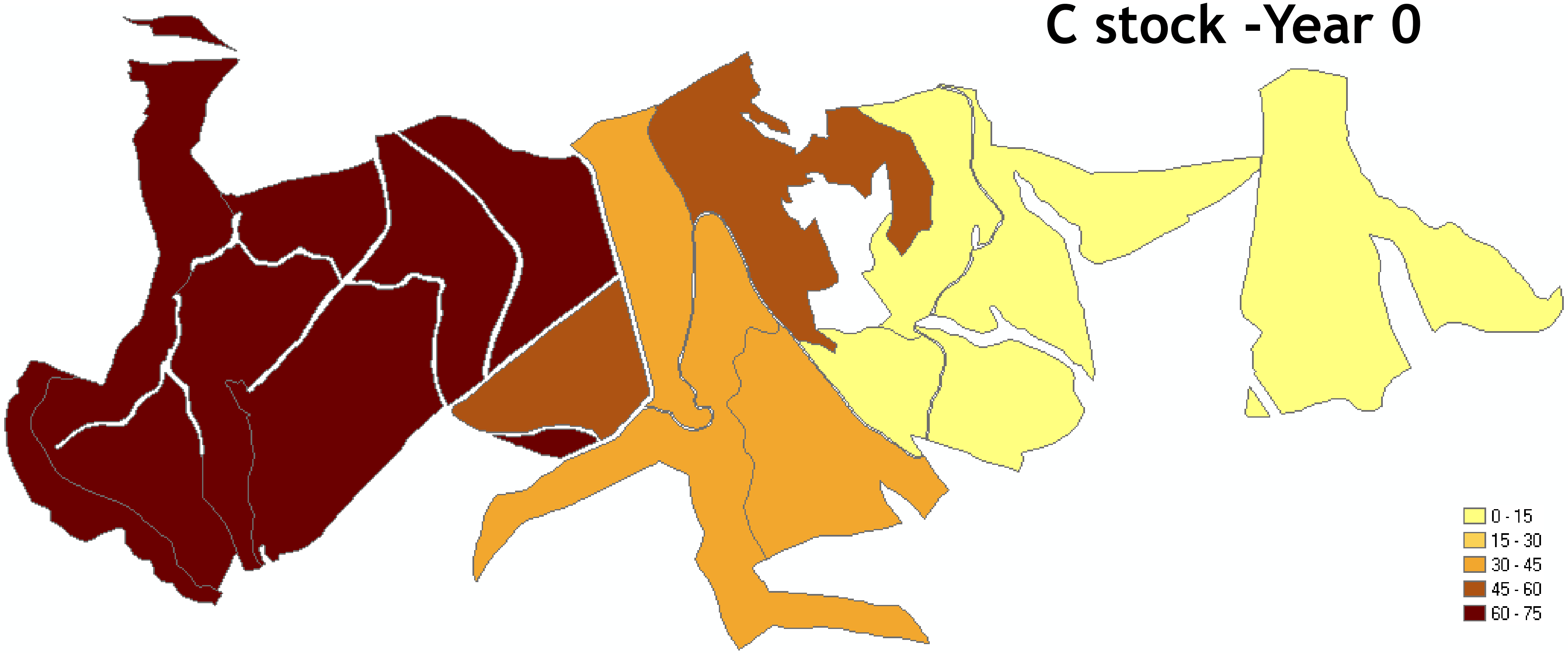
## ▪Landscape simulator

- ✓ Forest simulator focused on the simulation of all the stands included in a certain well defined region in which the stands are spatially described in a GIS
- ✓ The simulation is made on a stand by stand basis but outputs for the whole landscape are also provided, namely sustainability indicators
- ✓ It allows for the testing of the effect of spatial restrictions such as maximum or minimum harvested areas or maximization of edges of each stand according to a pre-established scenario

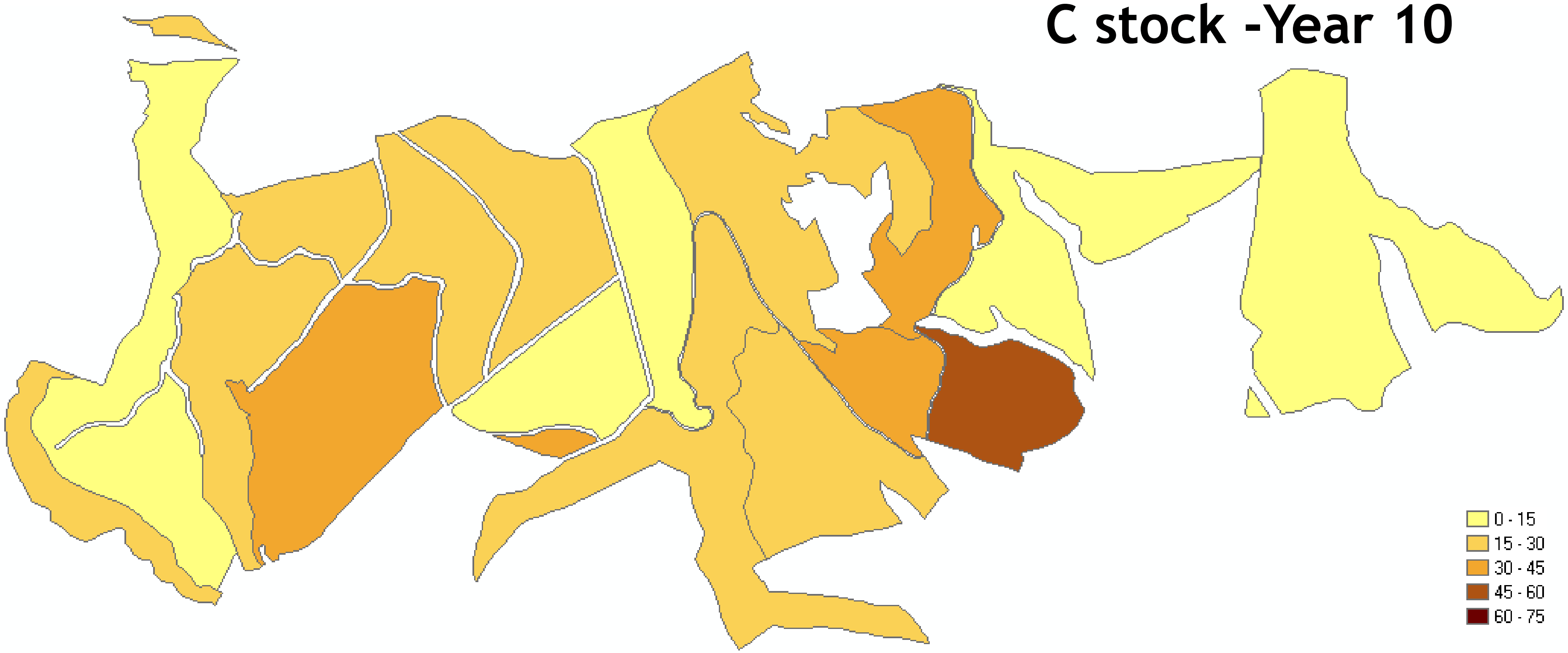

StudyArea_Age
Age_Aug_03
2 - 3
3 - 4
10 - 11
11 - 12


100
80
60
40
20
0
Year 0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Age class

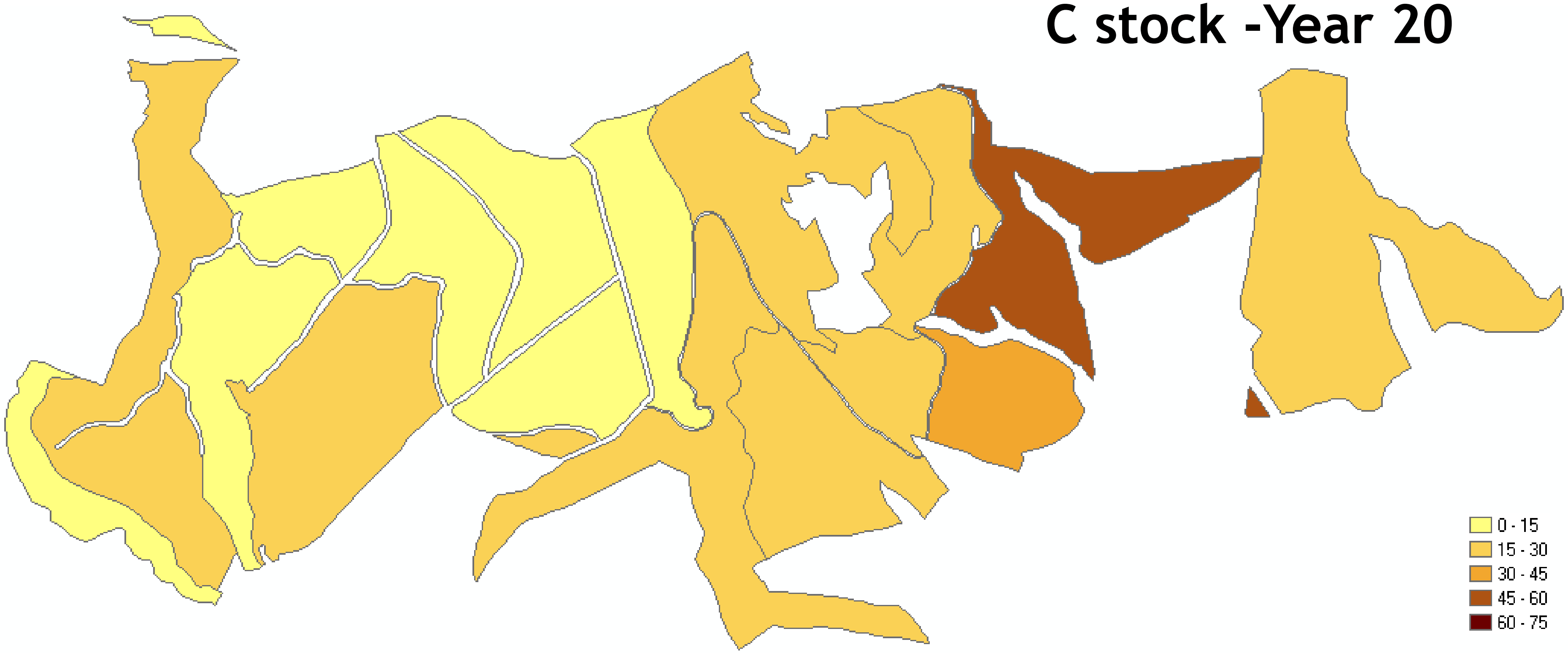
# C stock -Year 0

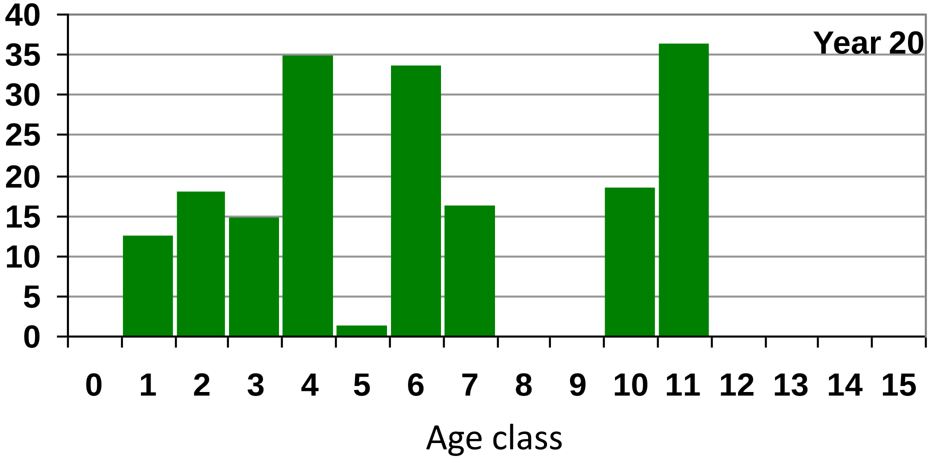


# C stock -Year 10

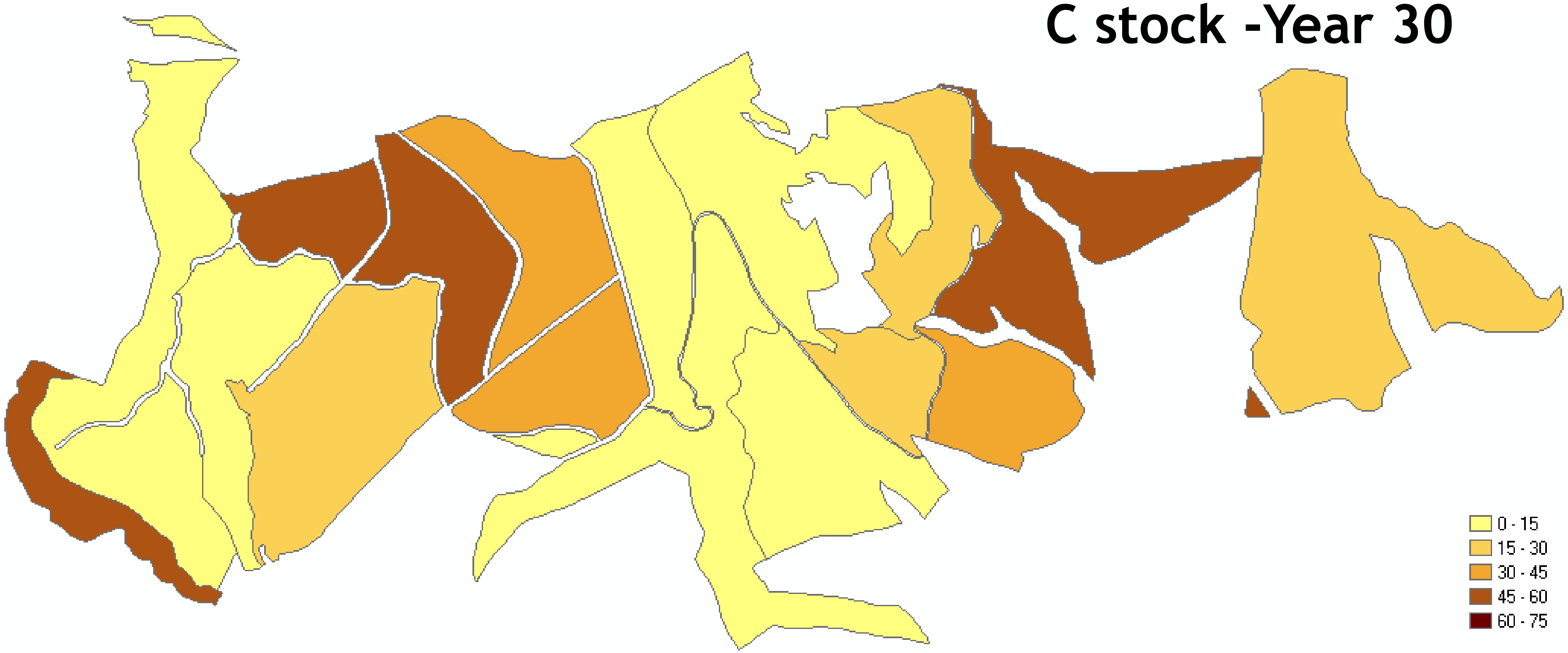


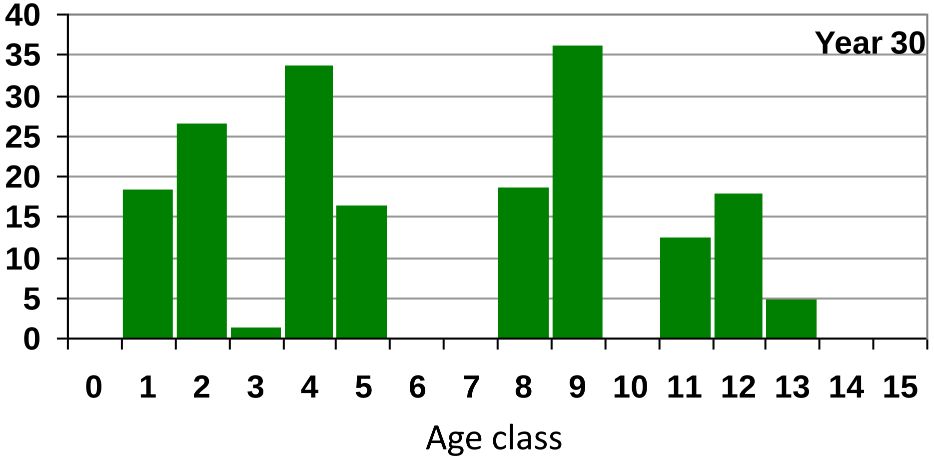

# C stock -Year 20



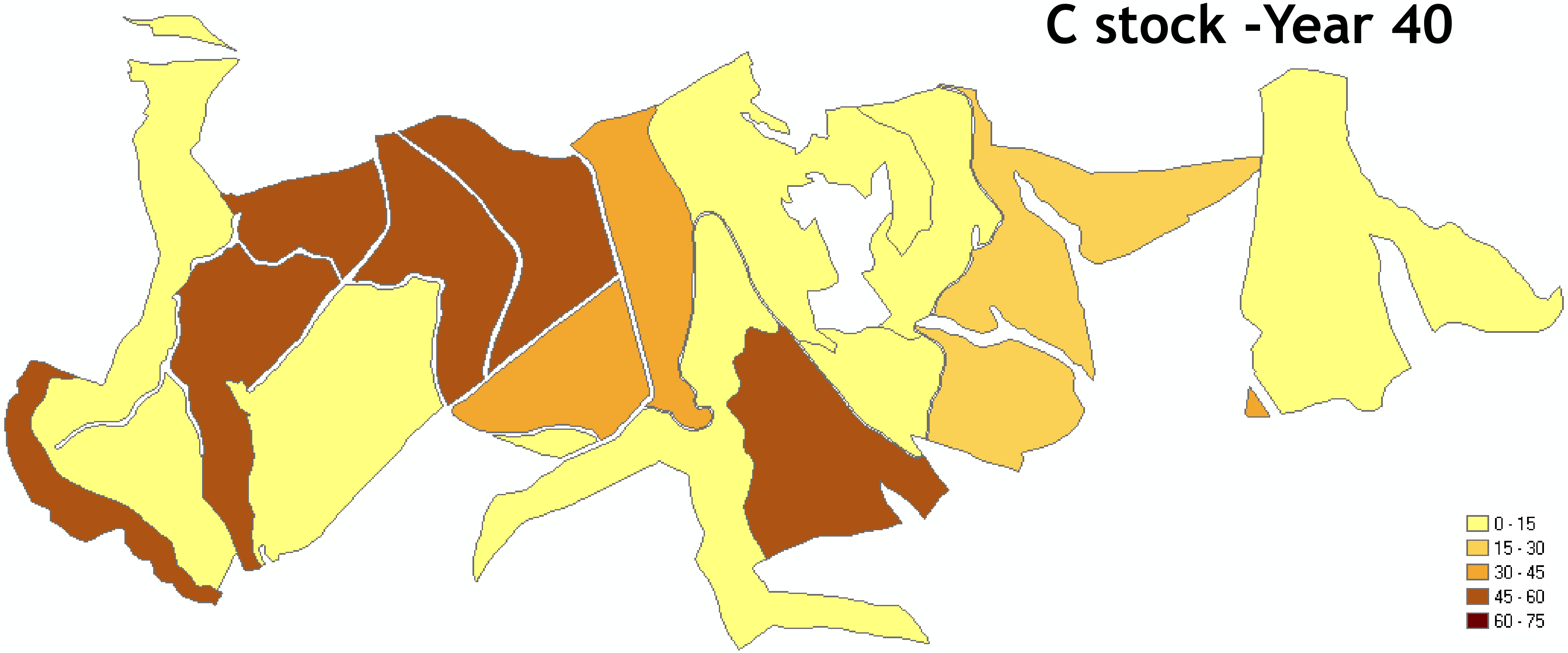



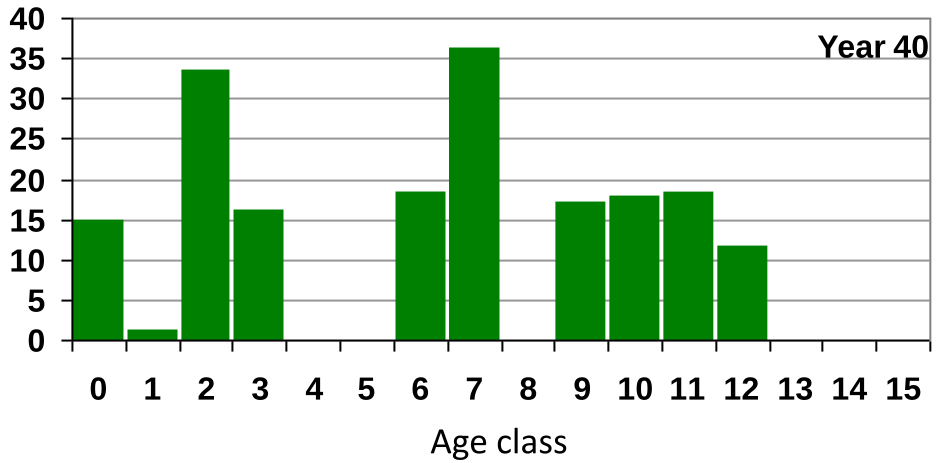
# C stock -Year 30



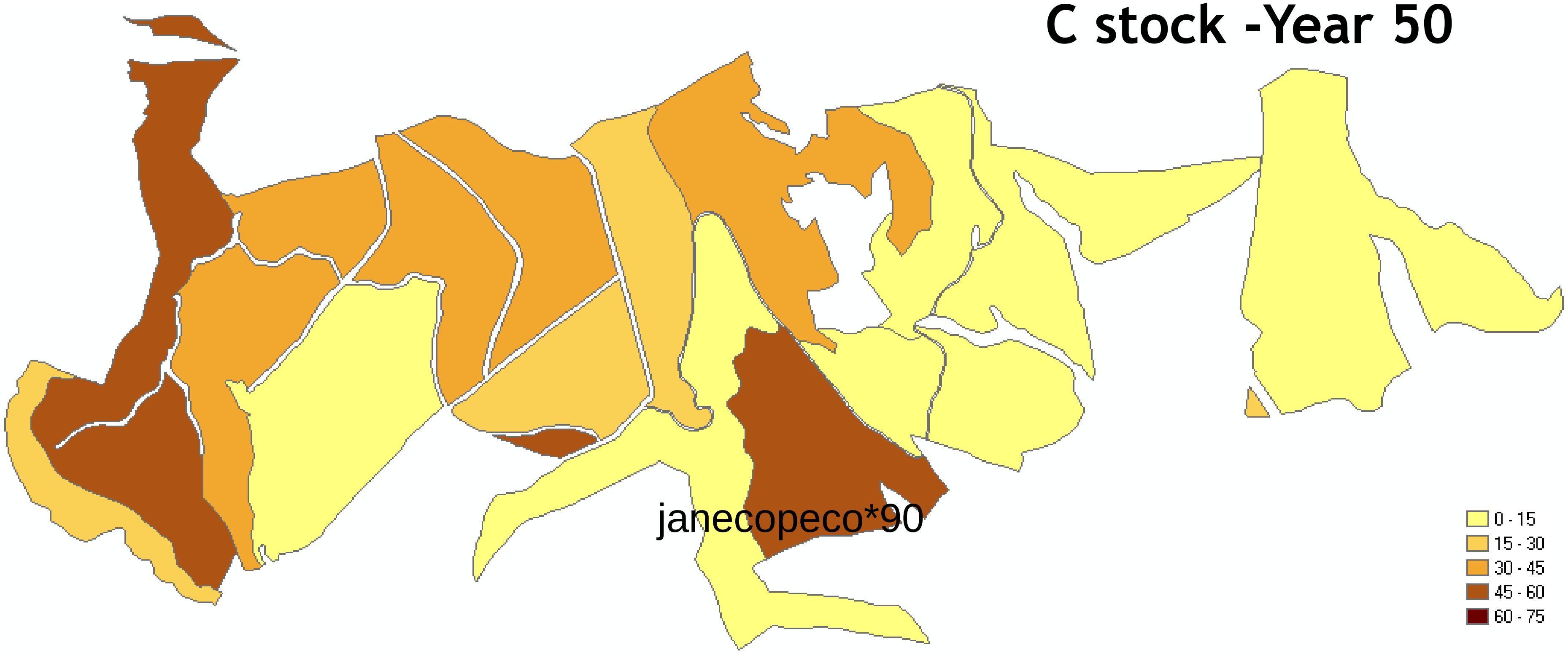



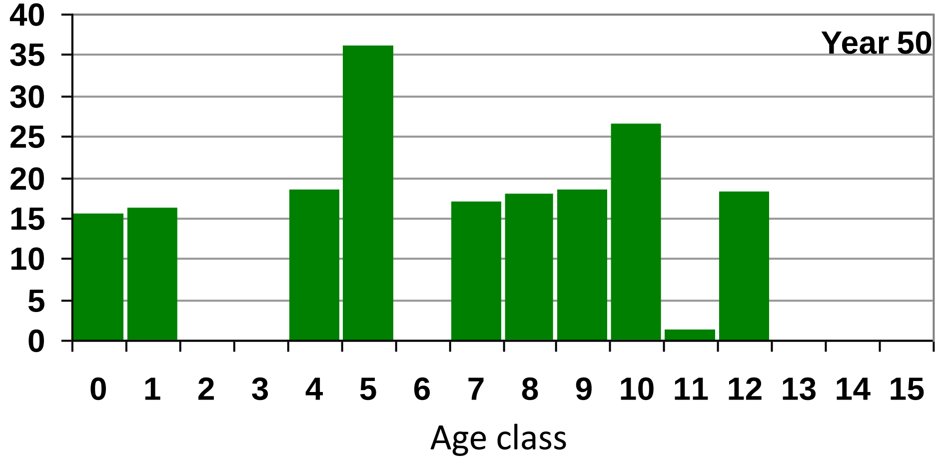
# C stock -Year 40



# C stock -Year 50



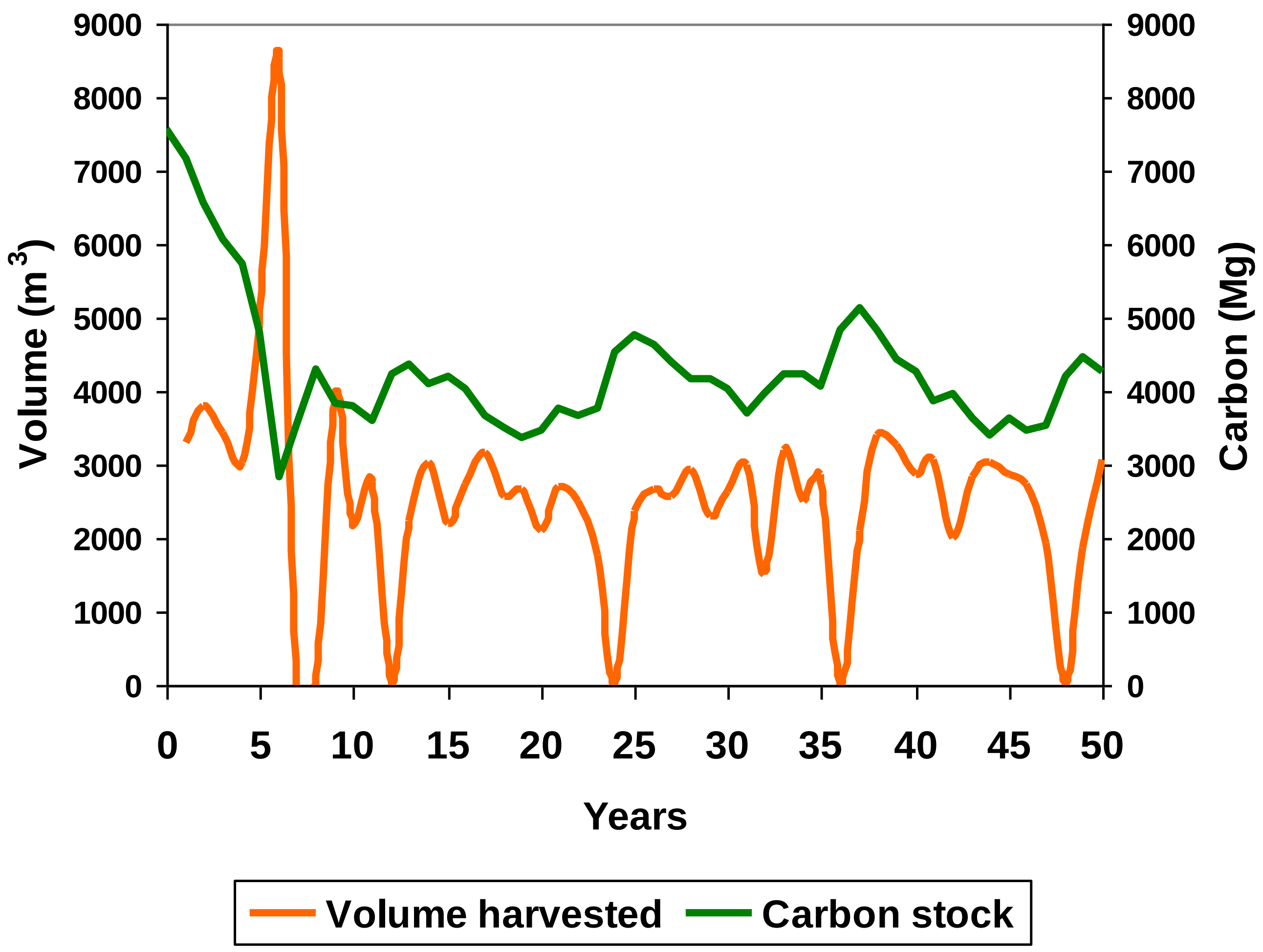



# ▪Global indicators of sustainability / ES

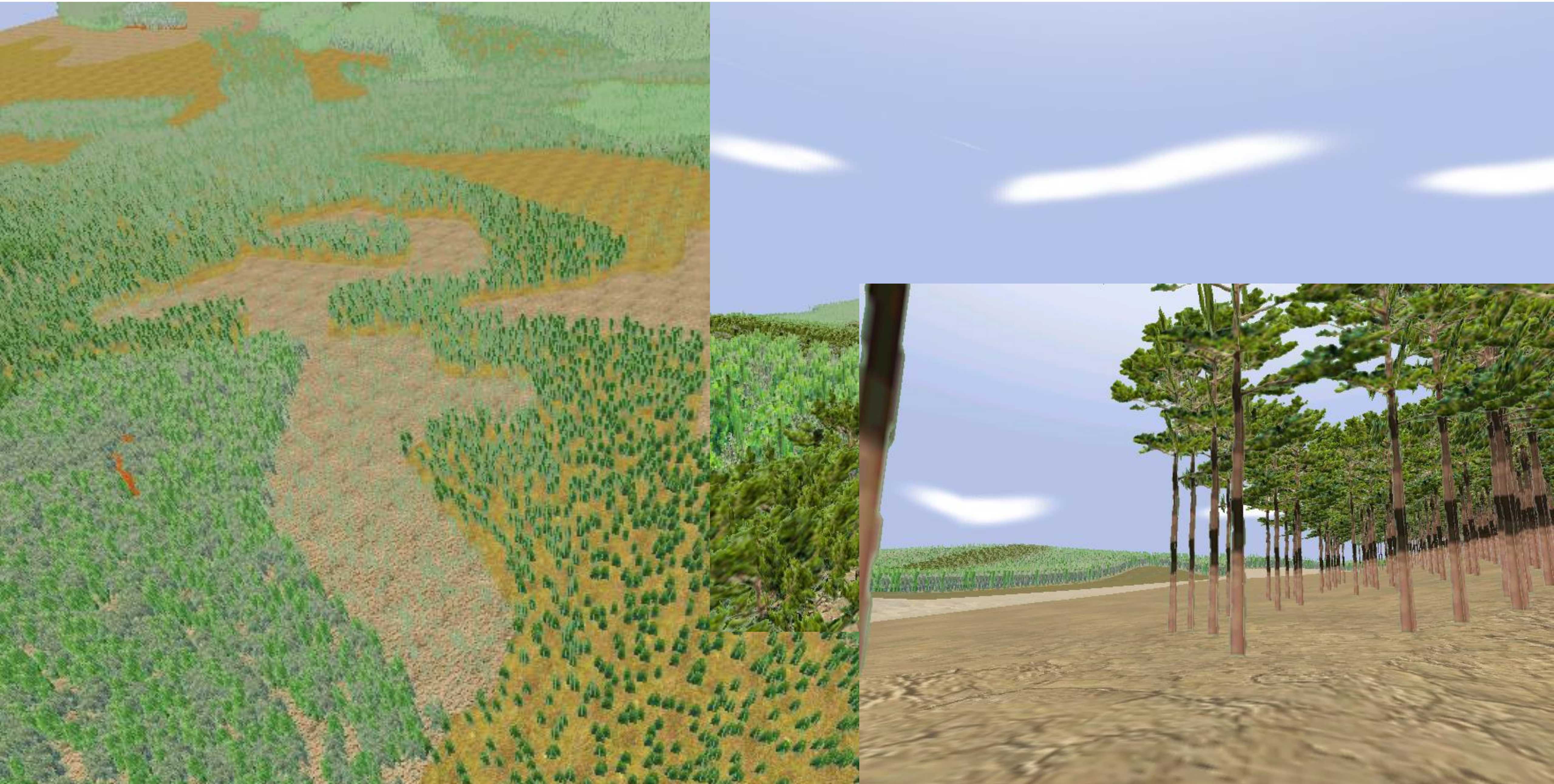
✓ Here we can compute, for each year, a large set of indicators of sustainability / ecosystem services

- Carbon stock and carbon sequestration
- Diversity indicators (e.g. Shannon-Winner for age classe, forest types, etc)
- Wages and employment
- % of areas dedicated to recreation
- Burned area
- Area with health problems
- ----

# Evolution of C stocks



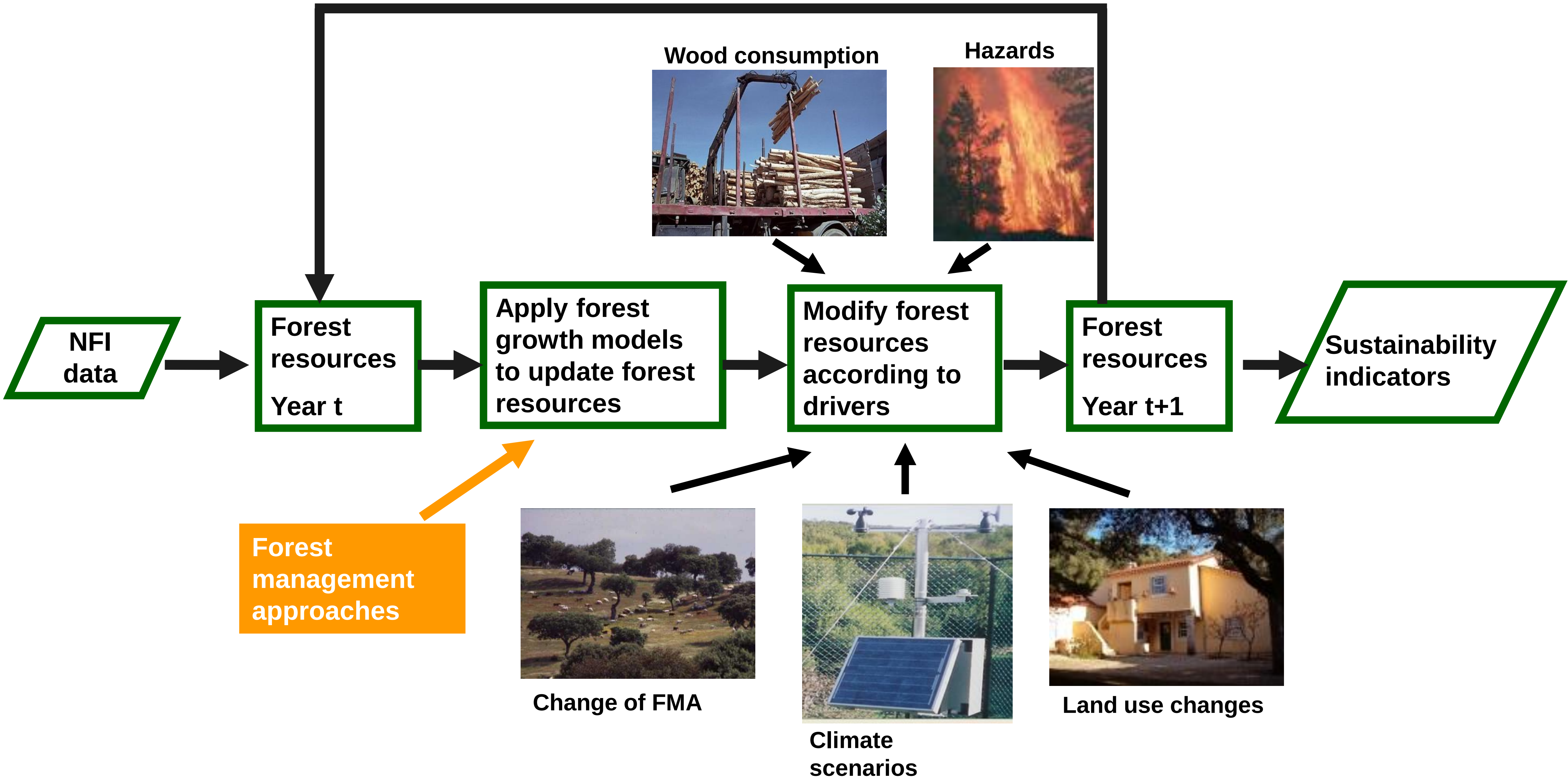
# Real-time 3D visualization of the landscape



- Regional simulators

# ▪Regional simulators

- ✓ Start with NFI information to characterize the forest resources in a region (e.g. NUT, country, Europe)
- ✓ use forest growth models to predict long-term development of forest resources in the region
- ✓ take into account the influence of a certain number of external variables – the drivers
- ✓ compute the subset of sustainability indicators that directly relate to forest resources



Wood consumption
Hazards
NFI data
Forest resources
Year t
Apply forest growth models to update forest resources
Modify forest resources according to drivers
Forest resources
Year t+1
Sustainability indicators
Forest management approaches
Change of FMA
Climate scenarios
Land use changes

# Example of standsSIM.sd

- Drivers:
  - → Annual wood harvest
  - → Area burned per year
  - → % of burned area that is harvested for industrial use
  - → Minimum age that allows industrial use after fire
  - → Minimum age for final harvest
  - → New areas planted every year
  - → % of area abandoned every year
  - → Climatic scenarios

# Implementation of 3PG in standsSIM-sd

- For climate change impacts standsSIM-sd use of the 3PGout+ model
- The input needed for the 3PG-based growth models is not available from the Portuguese NFI:
  - ➔ Soil texture, Fertility rating, Maximum available soil water
- How to solve the problem?
  - ➔ Persuade the Portuguese Forest Authority t… …ation in NFI (long term strategy)
  - ➔ Obtain the soil type from soil maps and estimate … …m that (short term strategy)

A problem really not solved!

# Drivers

- Wood demand
  - ➔CELPA statistics (consumption-import) till 2013 and maintenance of the 2013 value till 2037
    - Between 8 and 35% of the wood consumption has been imported in the period 2007-2013
- Forest fires
  - ➔Area burned based on historical series, considering two scenarios:
    - Business as usuall
    - Increased fires due to climate change

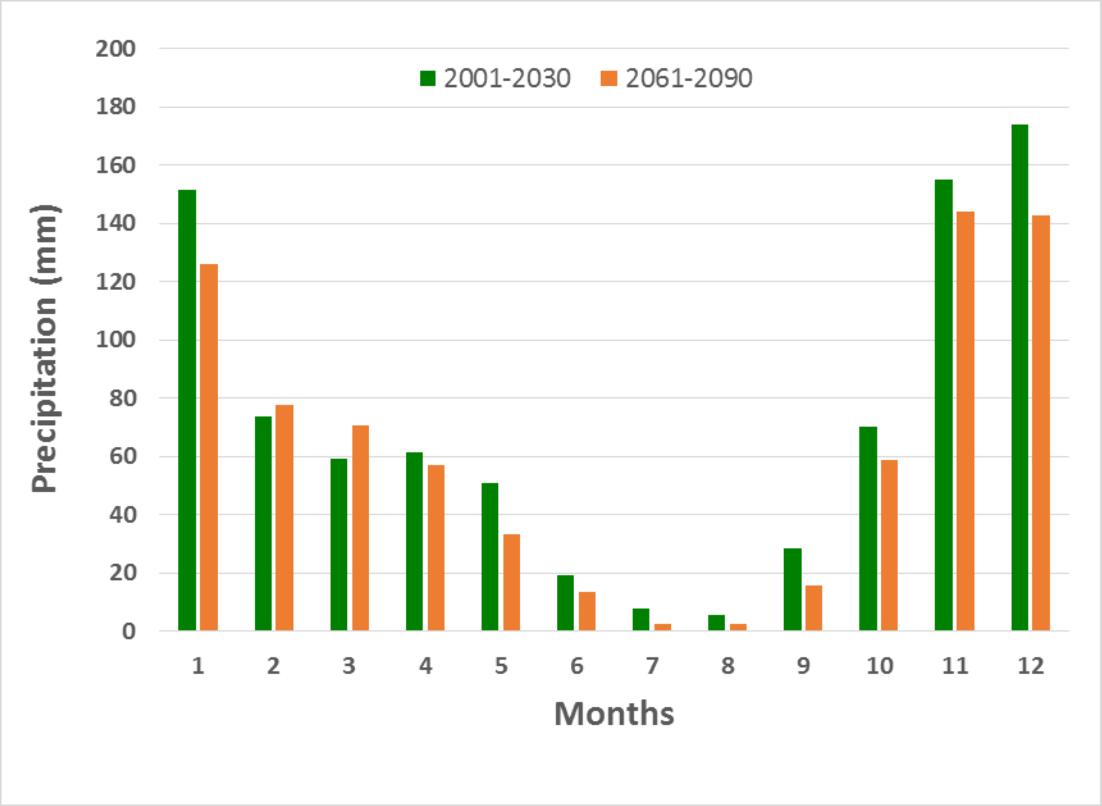
# Drivers (cont)

- Changes in forest management
  - ➔After harvesting, uneven-aged stands are converted to even-aged
  - ➔Just two FMAs, no options: UEAF and EAF
- Land use changes to/from other uses
  - ➔Annual area of afforestation based on our “expert judgement” (till 2014: 800 ha; 2015-2019: 1600 ha; 2020-2026: 1200 ha; nothing after 2027)
  - ➔No defforestation was considered

# Drivers (cont)

- Climate scenarios
  - ➔Scenario A1B
  - ➔Model HadRM (25 km) that has been found to be the most appropriate for Portugal
  - ➔Selection of the "metereological station" closest to each NFI plot and simulations made with averages for two periods:
    - 2001 – 2030
    - 2061 – 2090

# Precipitation in the two climate scenarios



# Scenarios

- A scenario is made up by the annual values for the drivers
- Other user options:
  - → minimum age for harvest (8 years)
  - → minimum age allowing industrial use after fire (5 years)
  - → % burned area harvested for industrial use (50%)
  - → Minimum fire recurrence (5 years)

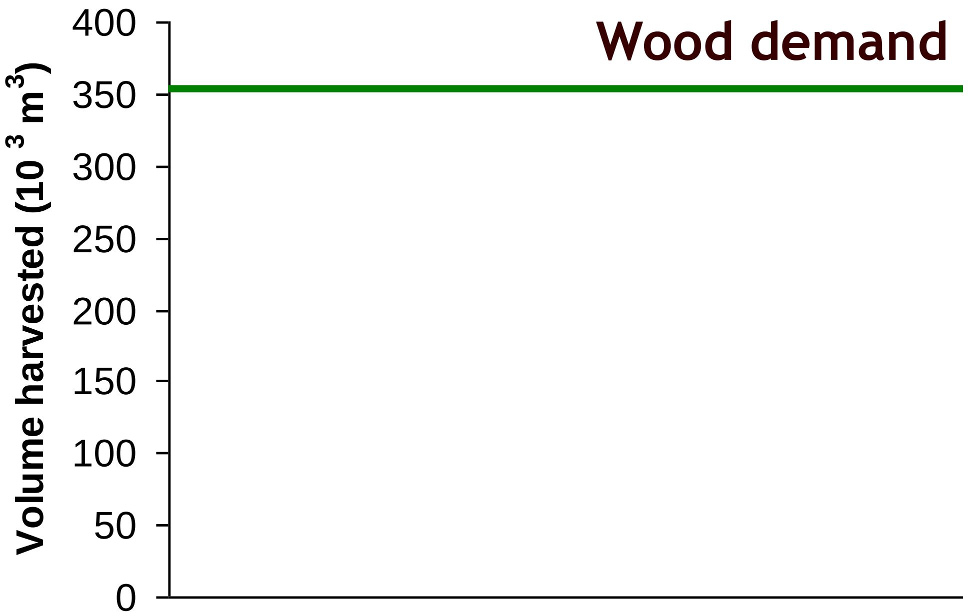
# Fire and harvesting modules

- All these modules work at “stand” level:
  - ➔A probability of occurrence of the event is estimated for each stand
  - ➔The event occurs or not by comparision with a random number
  - ➔In case the event occurs the simulator takes a specific action depending on the event

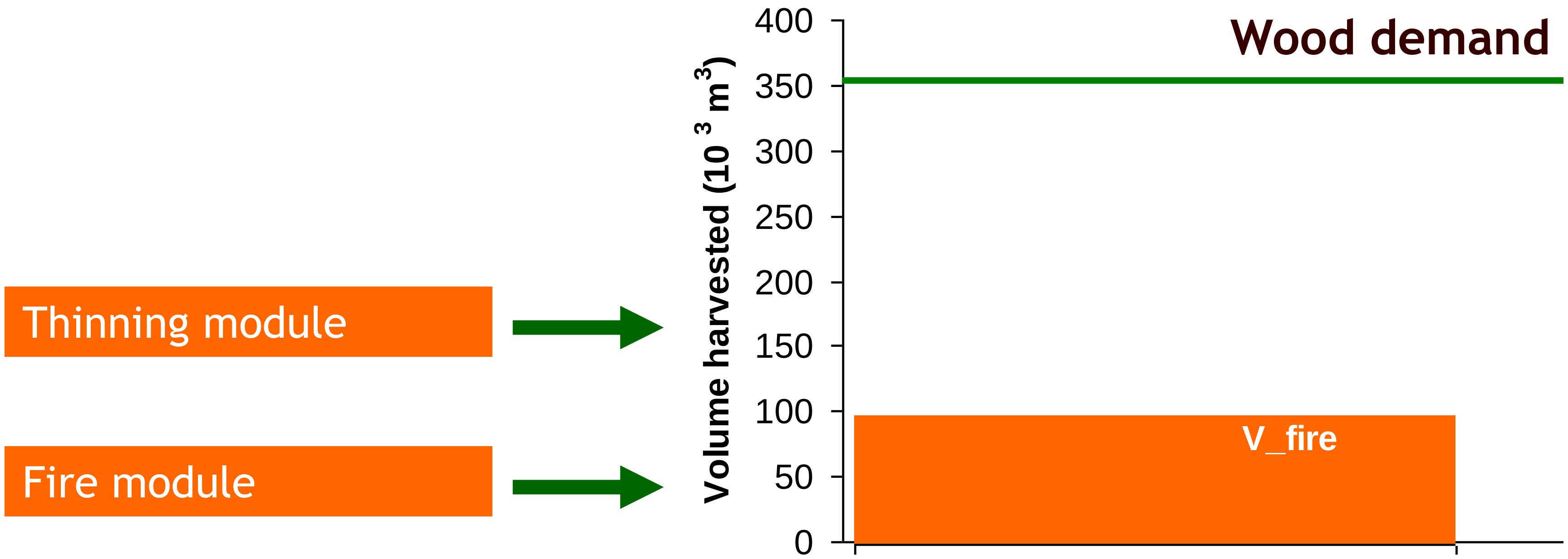
# How does the simulator work?

# ▪Implementation of the drivers

Fire module



# ▪Implementation of the drivers

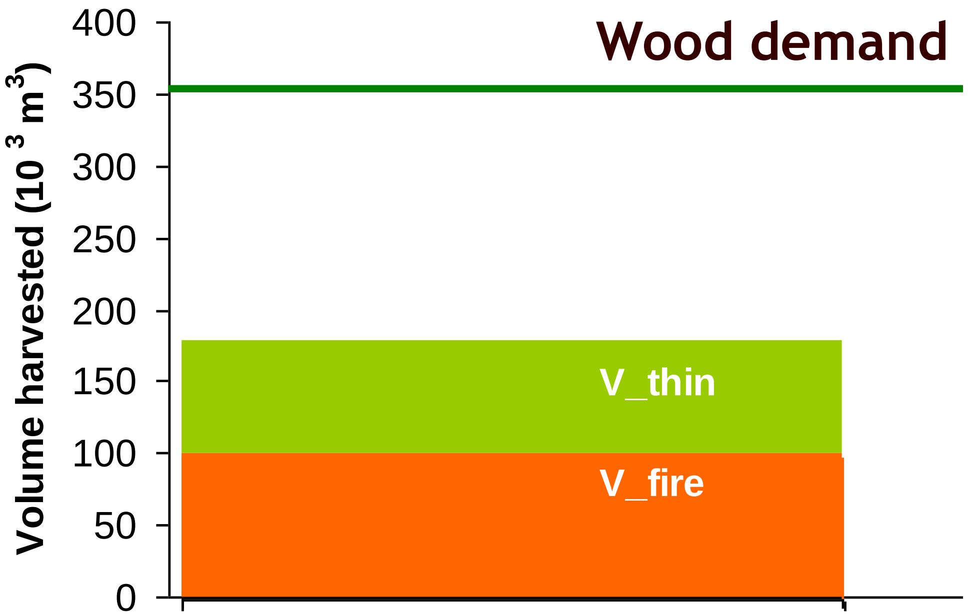


# ▪Implementation of the drivers

Final cut module

Thinning module

Fire module

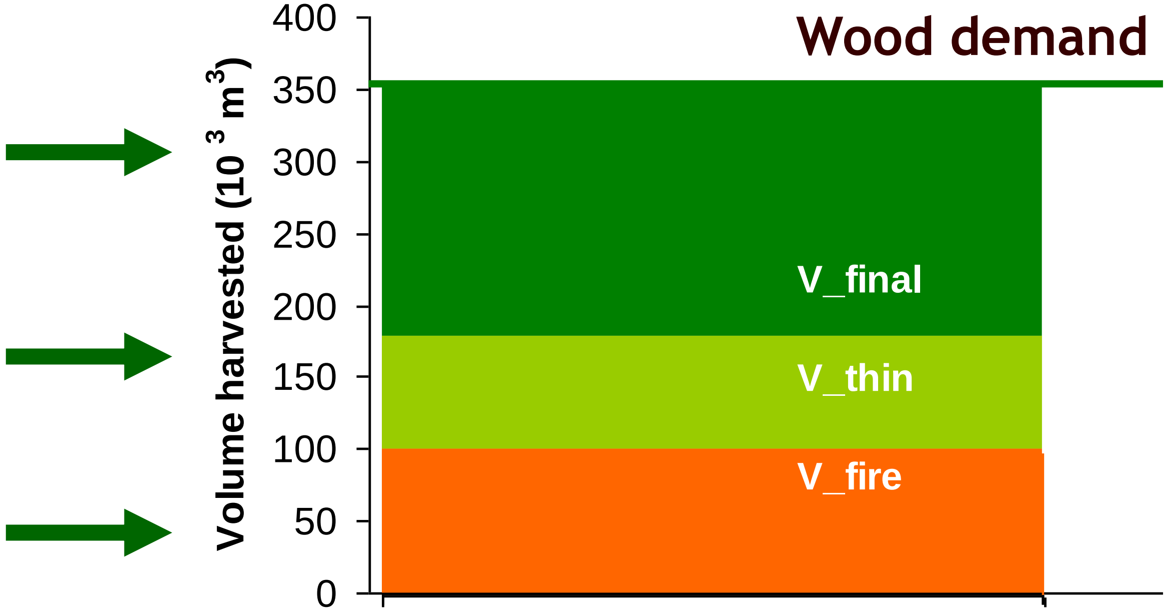


# ▪Implementation of the drivers

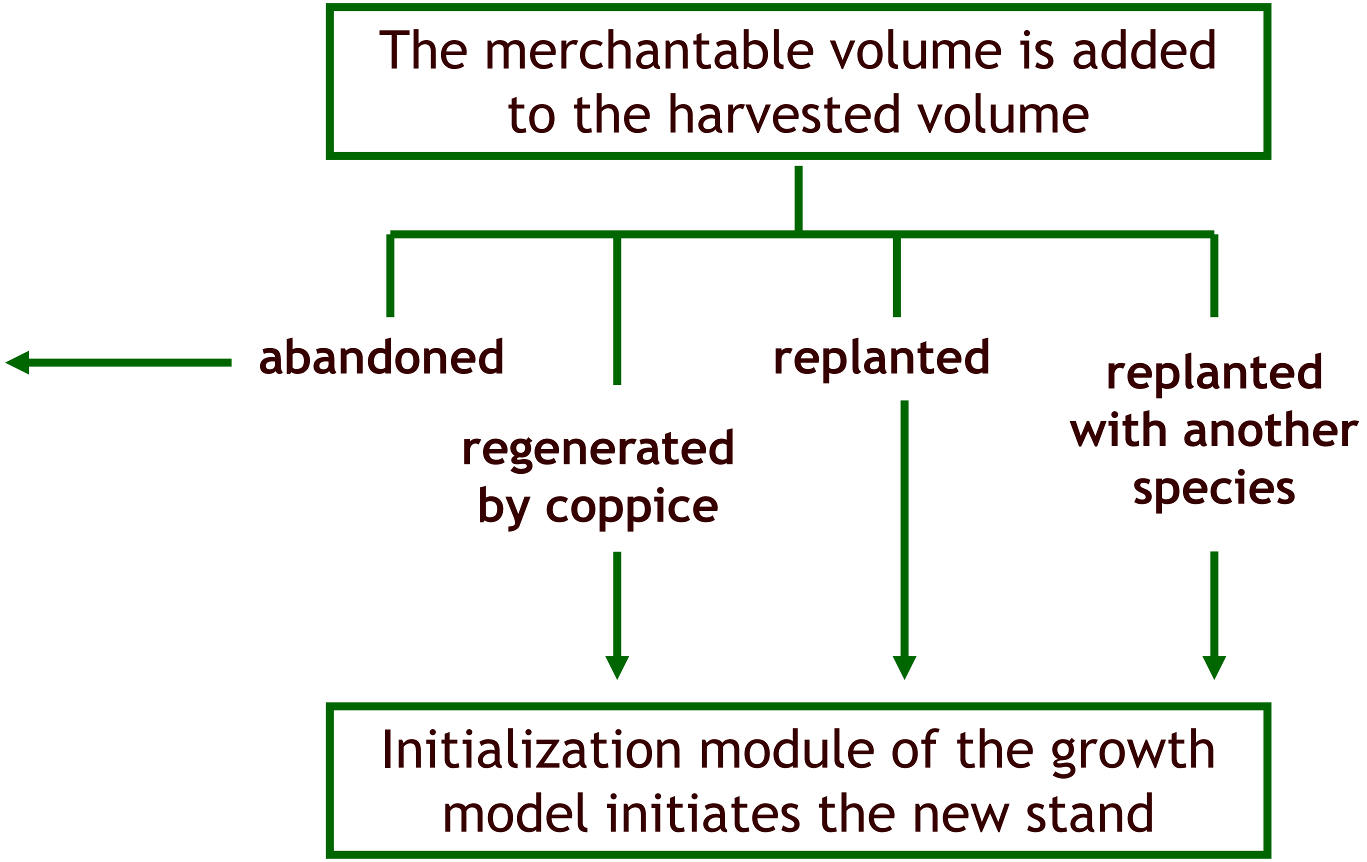
Clearcut module

Thinning module

Fire module

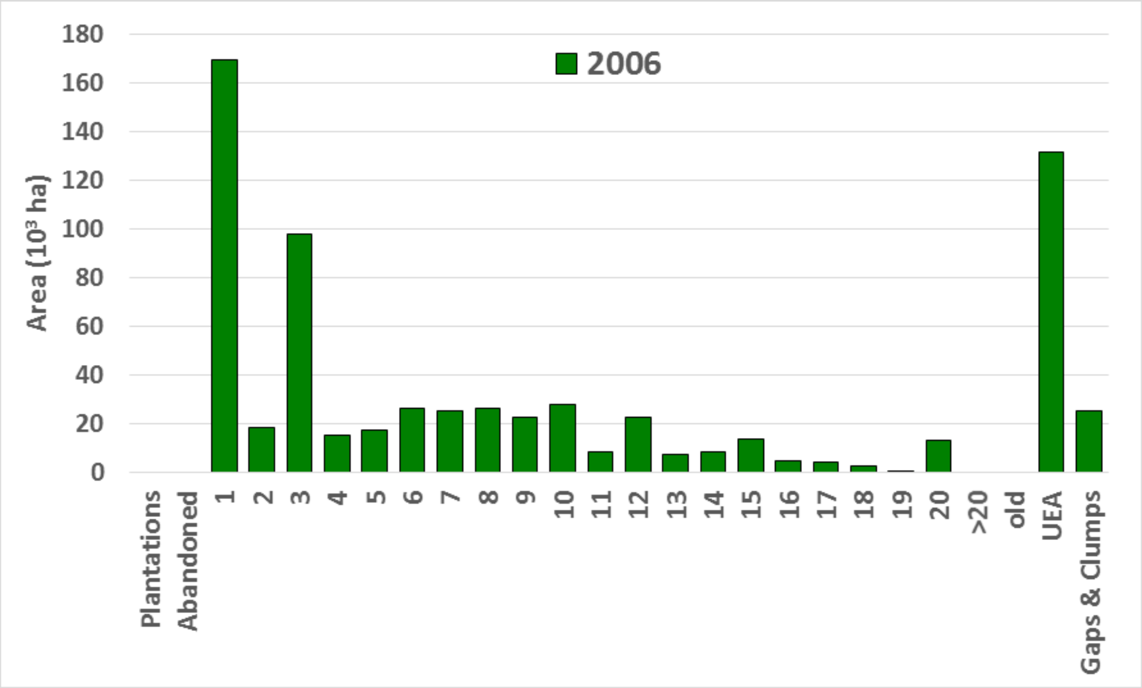


# Actions taken for a clearcut (as an example):



# Data used as input: NFI 2005-2006

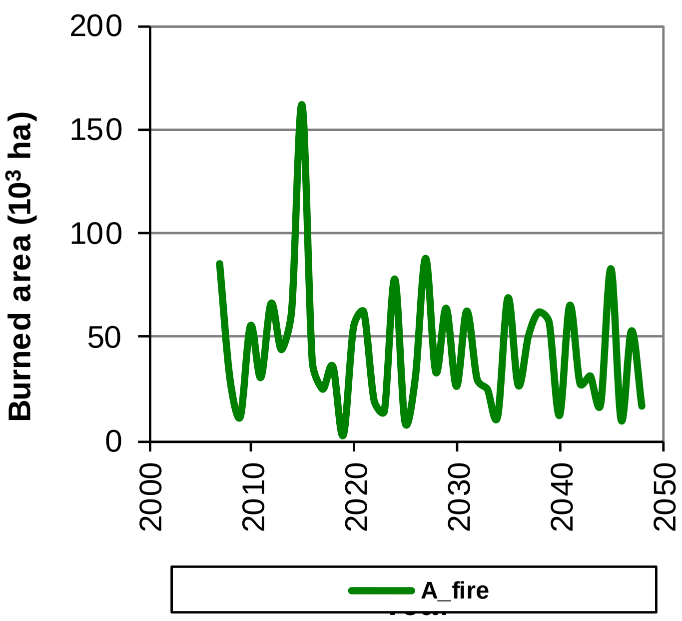
- Area of eucalyptus stands (pure): 663353 ha
- Number of plots: 1624
- Standing volume: 40.50 ($10^6$ $m^3$) (official is 43.22)

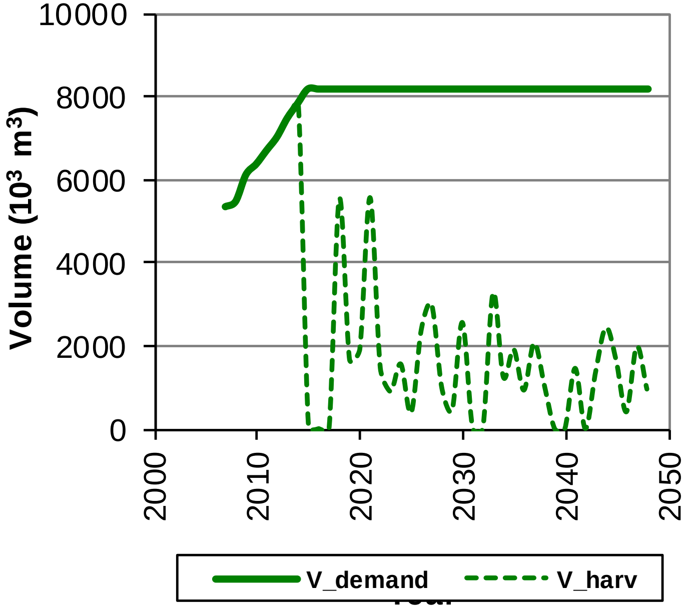


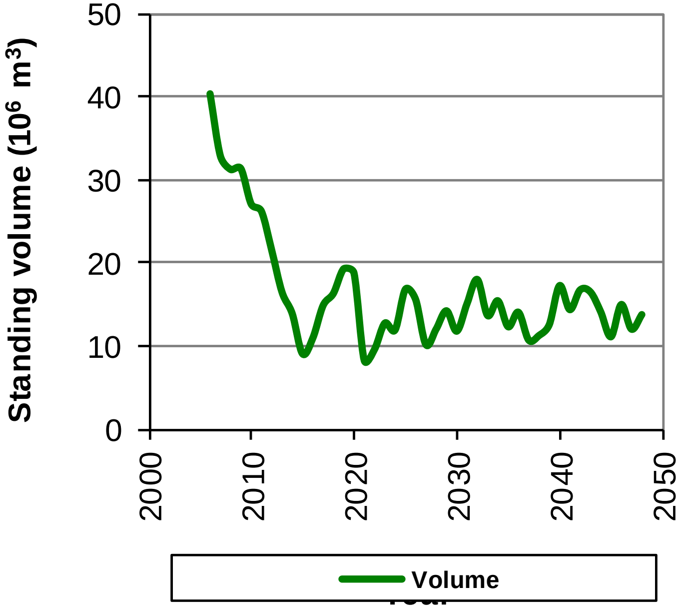
**No wood import**

**Climate 2001-2030**

**Fires BAU**



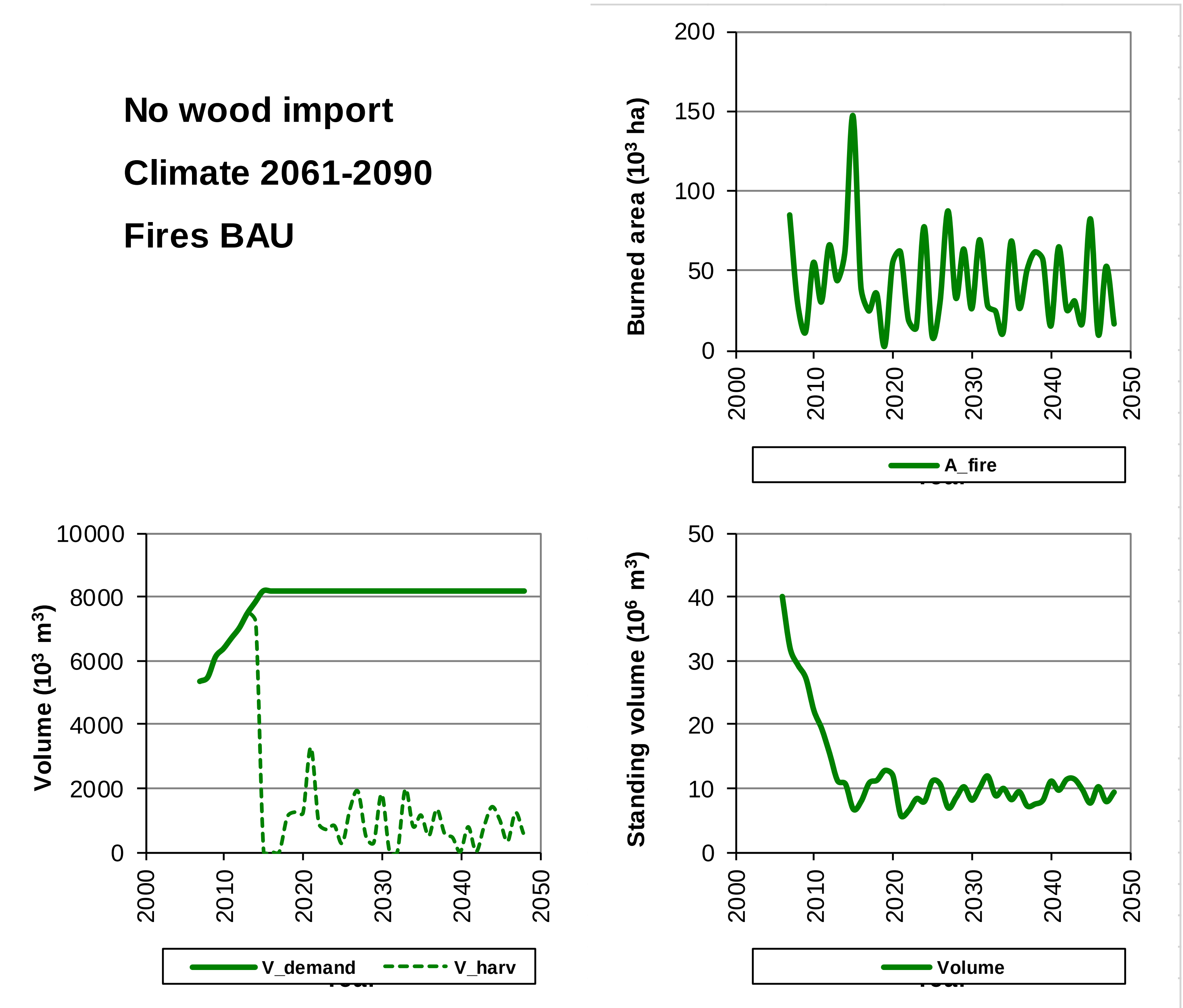



**No wood import**

**Climate 2061-2090**

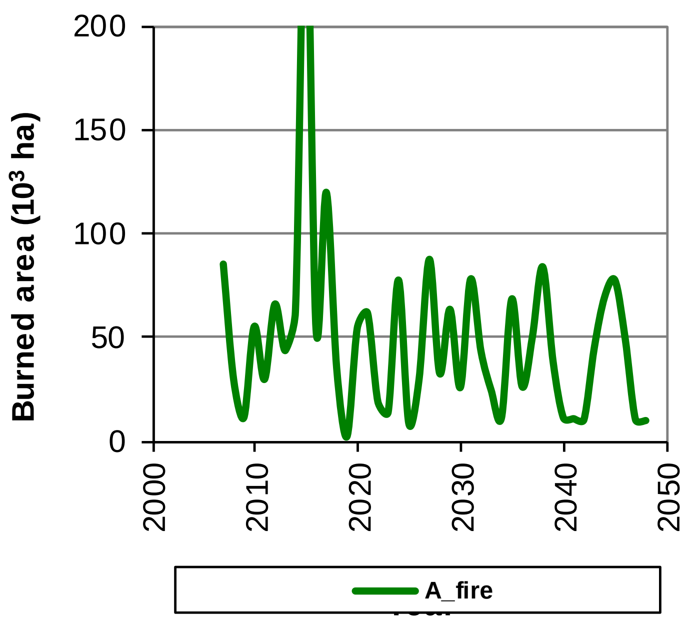
**Fires BAU**

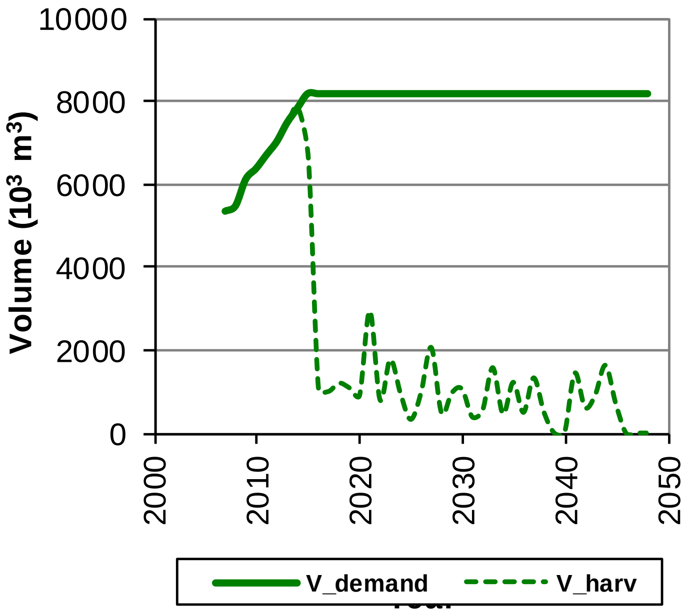


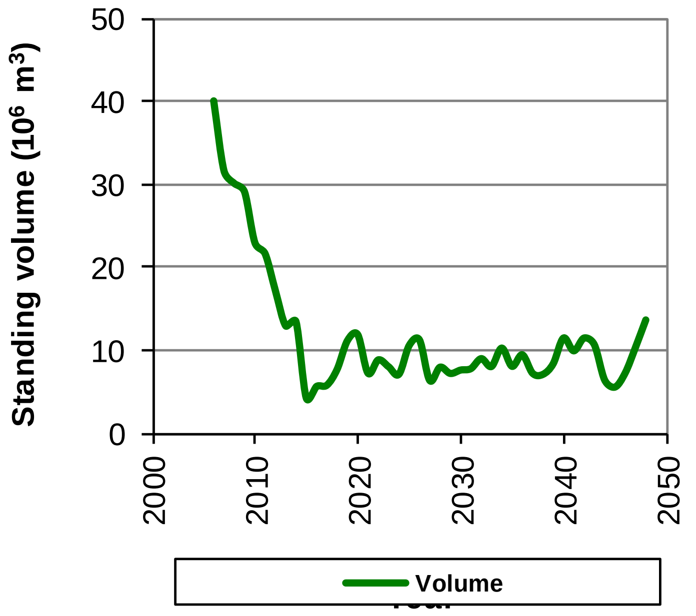
**No wood import**

**Climate 2061-2090**

**Fires IF**



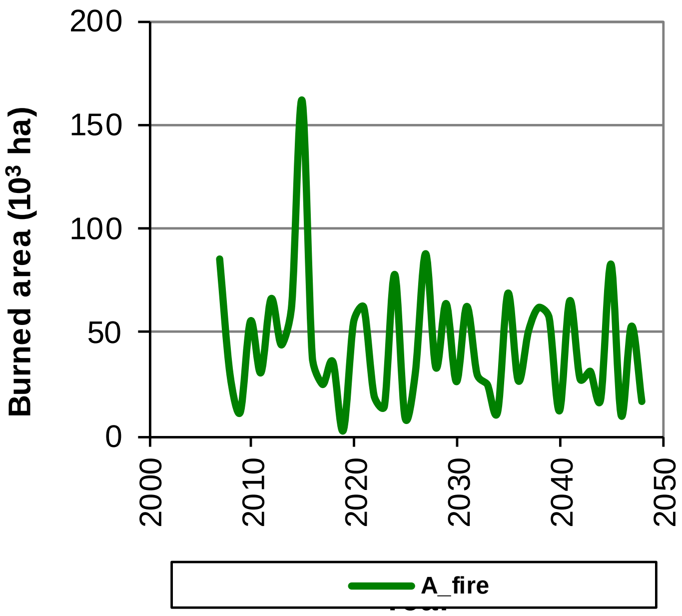



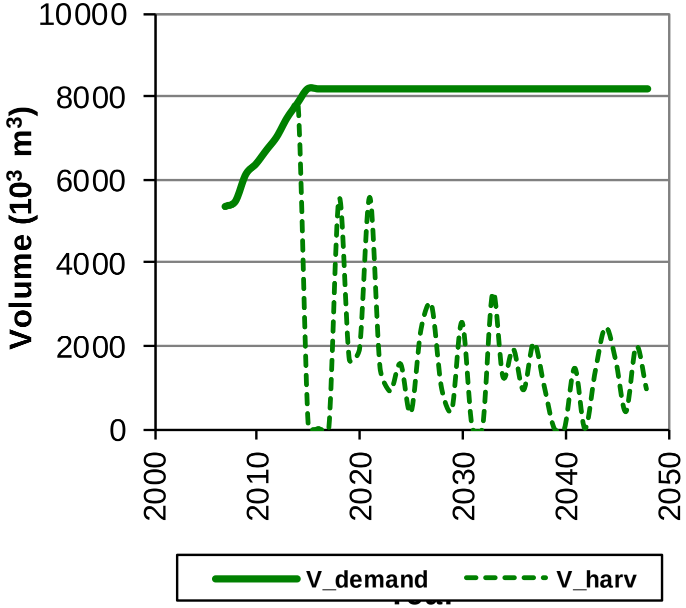



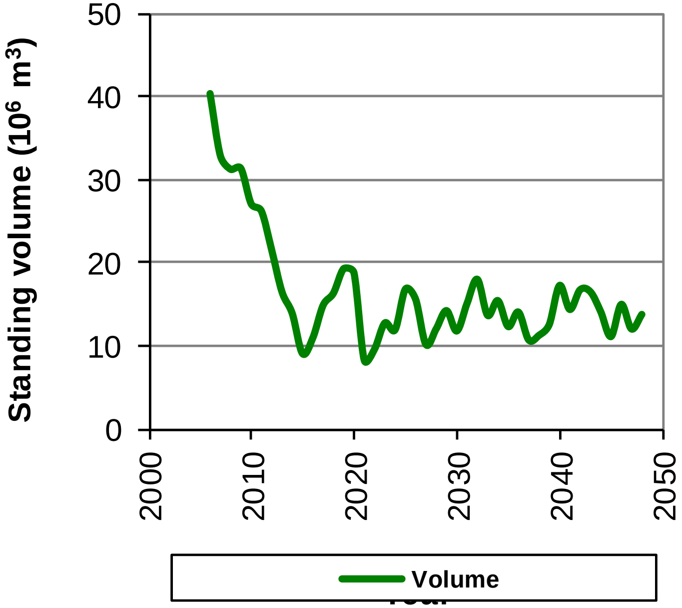
**No wood import**

**Climate 2001-2030**

**Fires BAU**



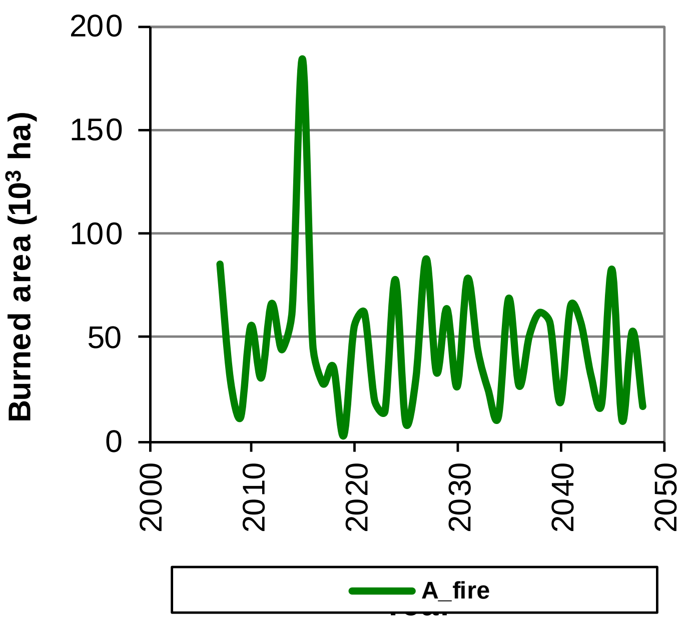



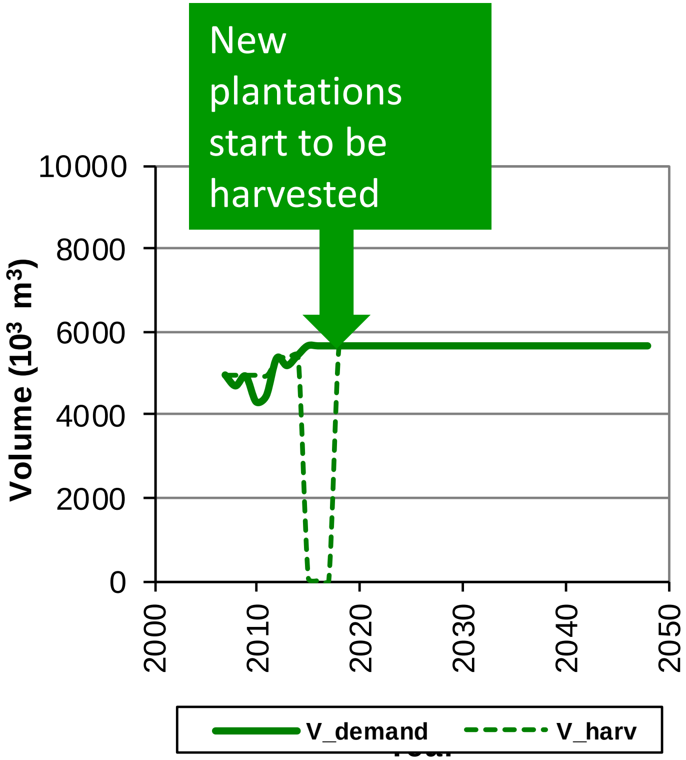



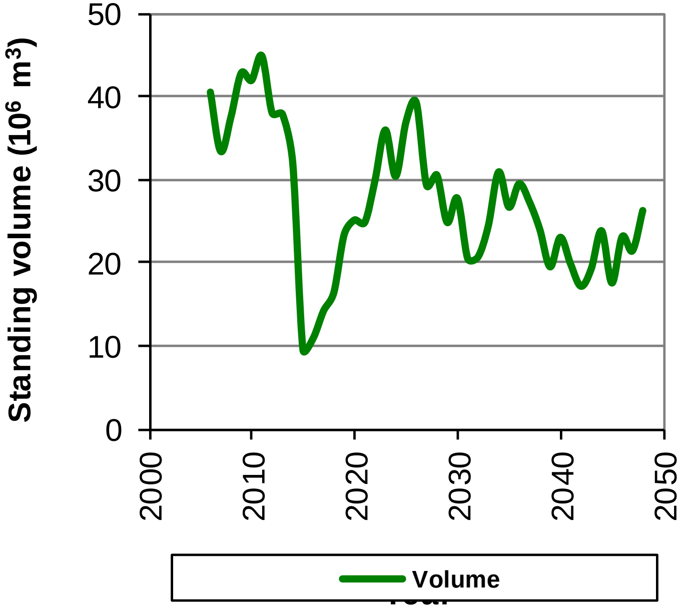
**Wood import**

**Climate 2001-2030**

**Fires BAU**



## ▪Some conclusions can be drawn from this study:

- ✓ Portuguese eucalyptus forest is in danger of becoming unsustainable
- ✓ The impact of climate change will emphasize this tendency
- ✓ Wood import and plantations can help to meet wood demand without puting the forest at risk
- ✓ Regional simulators, such as standsSIM-sd, are usefull tools to analyze forest sustainability as well as to find the best solutions to maintain it

## ▪Final comments

# ▪Good decisions on forest management?

✓ Depend on good decision support systems that include:
  - Forest inventory
  - Forest models (give answers to what if? questions)
  - Definition of the forest management approaches to test
  - Evaluation of the results using optimization and other OR techniques

✓ Where must the research efforts be put?

*Characterisation of each stand in the MU (values of state variables) at time t*

Forest inventory

*Forest simulator computer program*

*(includes a set of forest growth models)*

Forest simulator applied several times to each stand

*Simulation of several forest management alternatives (MA) for each stand*

*Prediction of wood & non-wood products and ecosystem services for each combination of FMA*

*Models and methods to select management options that may sustain conditions and outcomes of interest*

*(multiple criteria)*

Optimization and other OR techniques

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} corkA_{ijt}x_{ij} = CORKA_t,\ t = 1, \ldots, T$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} cones_{ijt}x_{ij} = Cones_t,\ t = 1, \ldots, T$$

Decision support system


Questions
?