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Combining 3D digitizing data and architectural modelling to simulate shoot growth and geometry in apple.

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Objectives and context

Digitizing is precise but time consuming:
- Few trees measured
- But digitizing can be performed on trees in agronomic conditions
- Can be used as reference for model validation

Simulations of tree development (MappleT) form 1yo to x-y-old based on Markov models for GU successions and branching
- Computational time can be long for running several consecutive years
- Do not integrate the agronomic conditions (especially pruning)
- Difficulty to compare the random trees generated with real trees.

Objectives.
- Use digitized trees at cycle n as input data and built tree at cycle n+x using statistical Markov models for terminal and axillary bud fates and apple tree geometrical characteristics
- Build a flexible tool for 3D reconstruction and evaluation of light interception of trees at any stage

Costes et al., 2008
Modelling description – digitizing data as input files

- Simplified digitizing methodology. (e.g. Massonet et al. 2008)

- Spatial coordinates of beginning and end of 1 year old shoot.
- Shoot type (vegetative, bourse shoot, inflorescence)
Modelling description – simulation of growing unit succession

- **Discretization of GU types** based on length (short, medium, long).

- **First order** transition probabilities after vegetative growth units.

- **Second order** transition probabilities after reproductive growth units. (fruit number is then computed using a fruit set parameter)

**Representation of the transition probability matrix**
(from Costes and Guédon, 2012).

- \((x_{ini}, y_{ini}, z_{ini})\)
- \((x_{end}, y_{end}, z_{end})\)

- Vegetative shoot
- Bourse shoot

- L: long
- M: medium
- S: short
- F: floral
- D: dead

\[
\begin{array}{ccc}
L & LF & M \\
M & MF & S \\
S & SF & D
\end{array}
\]

- Transition probabilities:
  - 0.51
  - 0.26
  - 0.15
  - 0.62
  - 0.26

\(x\), \(y\), \(z\): coordinate axes
Modelling description – simulation of branching pattern

- Hidden semi Markov chain formalisms (from Guédon et al., 2001; Costes and Guédon, 2002; Costes et al. 2008)

- Random choice of a sequence corresponding to the length of the GU

- GU internode number computed from allometric relationships.

\[ (x_{ini}y_{ini}z_{ini}) \]
\[ (x_{end}y_{end}z_{end}) \]

Vegetative shoot

Bourse shoot

Observation distribution

Transition frequencies

Occupation distribution

Generation of a collection of random sequences

\[ \text{DDDSDD, DDDSSSDD, DDDSSSSD, DDDSSSD, DDDSFSD, DDDFFS, DDDDFSD, DDDFFSF, DDDSDSS, DDD} \]
Modelling description – geometrical features

- Shoot length distribution to determine shoot length according to shoot type.

- Internode profile to locate all the branches along the 1 year old branch.

- Shoot geometry:
  - Branching angle for branches and after an inflorescence (mean value and standard deviation)
  - no shoot bending

\[ \alpha + \varepsilon \]

\[ \beta + \varepsilon \]

\[ \gamma + \varepsilon \]

\[ (x_{ini}, y_{ini}, z_{ini}) \]

\[ (x_{end}, y_{end}, z_{end}) \]

Vegetative shoot

Bourse shoot

\[ \text{GU length (cm)} \]

\[ \text{Probability} \]

\[ \text{Internode length (cm)} \]

\[ \text{Phytomer rank} \]

\[ \text{MaxIn} = \frac{\ln((\text{rank} - \ln(\text{sln})) / \ln(\text{sln}))}{1 + \exp\left(-\left(\frac{\ln((\text{rank} - \ln(\text{sln})) / \ln(\text{sln}))}{\ln(\text{sln})}\right)\right)} \]
Modelling description – simulation of leaf distribution along shoots

• Allometric relationships at shoot scale based on shoot length $L$ (short, medium, long) and type, and at leaf scale (Sonohat et al., 2006).

• At shoot scale: total leaf surface area ($TSA$), number of leaves ($LN$), internode length ($IN$) distribution and leaf area distribution along shoot.

• At leaf scale: length, width, surface area and distributions of leaf rolling angle and leaf inclination angle.

  ➢ Single leaf surface area ($LS$)

  \[ LS = \frac{TSA}{LN} \]

  ➢ Single Leaf length ($LL$) and width ($LW$)

  \[ LL = f(LS) \]

  \[ LS = f(LL) \]

  ➢ Leaf angles: Measurements of distributions of leaf rolling angle and leaf inclination angle by shoot type
• Model calibrated on the ‘Jubilé ‘cultivar (9 trees), data collected from 2007 until 2013.

• Growth units succession matrix estimated on sequences recorded on second and third order branches. (140 shoots)

• Geometrical features (branching angles, allometric relationships, length distribution) were recorded in 2013 on 8 years old trees.

• Fruit set was estimated on the 9 trees in 2013.
Model calibration

- Calibration of the hidden semi Markov model.

- Performed on around 100 branching sequences collected in 2013.

- Model estimation with openalea plateform.

- A unique model for each growth unit was used.

- Simple patterns were observed.

- Branching pattern only adapted for « small size GU » (old tree).
Model simulation and validation

- 2 trees digitized in 2013 and 2014 (8 year-old).
- 2013 data were used as input files and simulations (15 random trees) were compared to 2014 data.
- A modeling framework coupling the ‘simulation’ model, a 3D visualization software and a light interception model (RATP, Sinoquet et al. 2001) was built.
- Validations were performed on shoot demography, leaf area distribution and light interception.

- Except for the probability of flowering occurrence (ON, OFF trees), all the parameters were identical for the two trees.

Year N

*Input tree*

Simulation of tree growth « Rebuild tree model »

Tree 3D visualization « Vegestar »

Year N+1

*Simulated trees*

Simulation of light interception « RATP »

Annual shoots

1-year-old shoots
Model validation, shoot demography and leaf area (tree 1)

- Observed tree

<table>
<thead>
<tr>
<th>Leaf area (m²)</th>
<th>GU number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>3.39</td>
</tr>
<tr>
<td>Simulated (n = 15)</td>
<td>3.17</td>
</tr>
<tr>
<td></td>
<td>+/- 21.3</td>
</tr>
</tbody>
</table>

- Simulated trees

Random seed 602

Random seed 601
Model validation, light interception inside the canopy (tree 1)

• Observed tree

![Observed tree visualization]

- STAR at the tree scale
<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Simulated n = 15</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.350</td>
<td>0.349 +/- 0.011</td>
</tr>
</tbody>
</table>

• Simulated trees

![Simulated trees visualization]

- Voxel STAR frequency
- Random seed 602
- Random seed 601
Model validation, shoot demography and leaf area (tree 2)

- Observed tree

- Simulated trees

<table>
<thead>
<tr>
<th></th>
<th>Leaf area (m²)</th>
<th>GU number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>4.42</td>
<td>451</td>
</tr>
<tr>
<td>Simulated (n = 15)</td>
<td>4.60 +/- 0.18</td>
<td>492.1 +/- 26.2</td>
</tr>
</tbody>
</table>

Random seed 600

Random seed 605
Model validation, light interception inside the canopy (tree 1)

- Observed tree

<table>
<thead>
<tr>
<th>STAR at the tree scale</th>
<th>Observed</th>
<th>0.386</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated n = 15</td>
<td></td>
<td>0.332 +/- 0.008</td>
</tr>
</tbody>
</table>

Random seed 600

Random seed 605

Voxel STAR Frequency

Simulated trees (15) Observed tree
Multi-years simulations

- The model is able to simulate tree growth over years.
  - 2015 digitizing data are needed to validate the model on a 2 years time step
  - The tree response to pruning should be integrated.
  - A branch bending submodel (Costes et al. 2008) should be integrated to simulate branch geometry over years

*End 2013 (observed tree)*

*2014 (simulated tree)*

*2015 (simulated tree)*

*2016 (simulated tree)*
Conclusions and perspectives

Development of a new modelling approach
- Including and adapting already used statistical models
- Linked with a light interception model
- Allowing the valorisation of time consuming digitizing data.

First calibration of the model
- On Jubilé cultivar (old tree).
- At different scales (whole tree, voxels)

Limits and forthcoming works.
- Model calibration is time consuming
- Testing the relevance of multi-years simulations
- Testing the genericity of model parameters for other tree ages
- Necessity to take into account pruning to deal with agronomic cases of study.
Thanks you for your attention

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