Influence of the variation of geometrical and topological traits on light interception efficiency of apple trees: sensitivity analysis and metamodelling for ideotype definition.

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INRA
SCIENCE & IMPACT

Apple tree architecture

- results from complex and dynamic interplays between topology and geometry
- plays a key role in 3D foliage distribution
- determines efficiency of light interception
- Influences water transport and transpiration
- influences carbon acquisition and allocation
- affects reproductive growth

An optimised architecture can help in

- improving fruit quality
- increasing agricultural yield
- reducing use of unnecessary chemical products

Difficulties for field experiments

- scale and complexity of apple tree structure
- number of tree individuals
- growth period

Advantages of computational modelling

- running time- and resource-saving virtual experiments
- analyzing possible tree architectures
- setting optimal targets for genetic and physiological studies

Light interception

- Mainly results from:
  - 3D foliage distribution
  - Tree architecture
- Major process that affects:
  - Water transport and transpiration
  - Carbon acquisition
- Hence, influences:
  - Plant growth
  - Yield

→ **Interest in optimizing light interception**

Optimizing light interception

- Manipulation of tree architecture can be achieved through:
  - Agronomic practices (training systems, pruning)
  - Genetics (cultivars)
- Two aspects of tree architecture to consider
  - Geometry
  - Topology

both under genetic control

Optimizing light interception

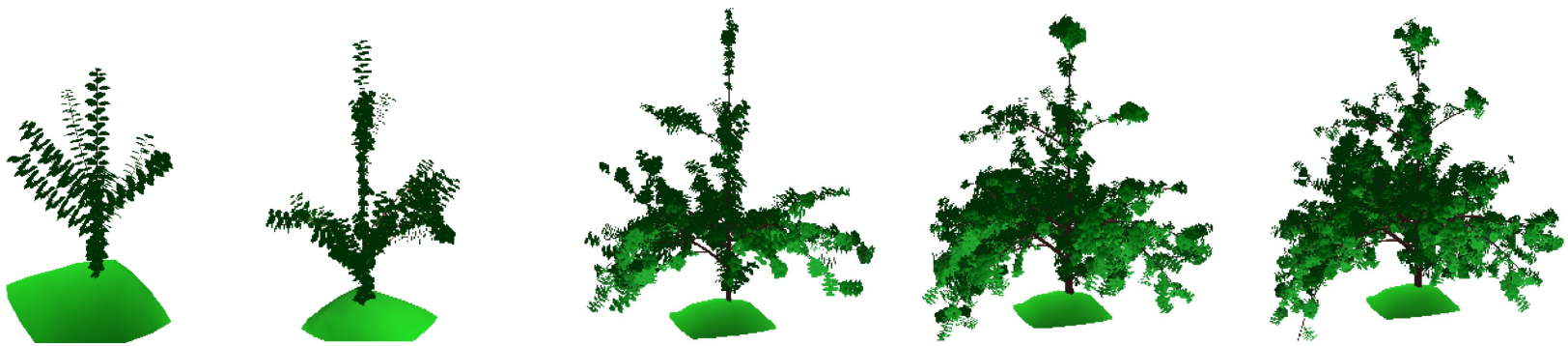
- We propose a *in silico* framework to tackle this:
  - MAppleT (Markov Apple Tree) [Costes *et al.*, 2008]
  - STAR (Silhouette to Total Area Ratio) [Oker-Blom and Kellomaki, 1983]
  - MµSLIM (Multi-Scale Light Interception Model) [Da Silva *et al.*, 2008]
- 2 sets of virtual experiments
  - Influence of geometrical traits variation with fixed topology
  - Influence of topological traits variation with fixed geometrical parameters
  - Range of variability from segregating population of 111 apple hybrids [Segura *et al.*, 2008]
- Sensitivity analysis & Metamodelling [Faivre *et al.*, 2013]
  - GAM
  - PLMM

MAppleT: Markov Apple Tree

An architectural model of apple tree

- Based on the l-sytem paradigm
- Architecture is generated by HSMC and MC models
- Biomechanic model for branch bending
- Available within OpenAlea framework

Can generate the architecture of apple trees over multiple years of growth



Silhouette to Total Area Ratio

- Ratio of Projected Leaf Area to Total Leaf Area

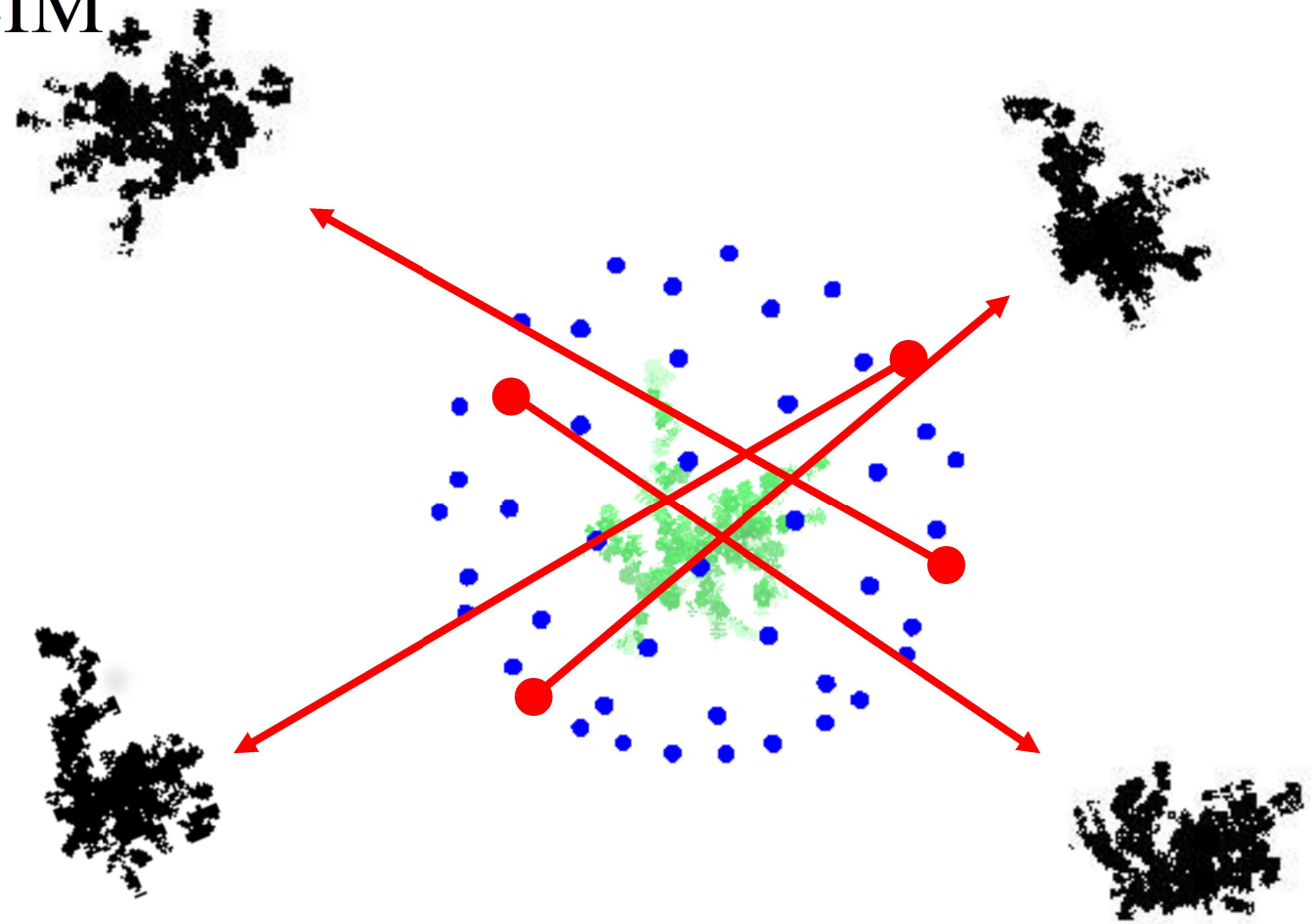
$$STAR_{\Omega} = \frac{PLA_{\Omega}}{TLA} \qquad \Omega = direction\ of\ incident\ light$$

- Directional measurement of light interception efficiency
  - Take leaf overlapping into account
  - Directly connects to photosynthesis computation through LAI
  - Can be integrated over multiple directions

$$STAR = \sum_{\Omega} STAR_{\Omega} . \omega_{\Omega} \qquad \omega_{\Omega} = weight\ of\ direction\ \Omega$$

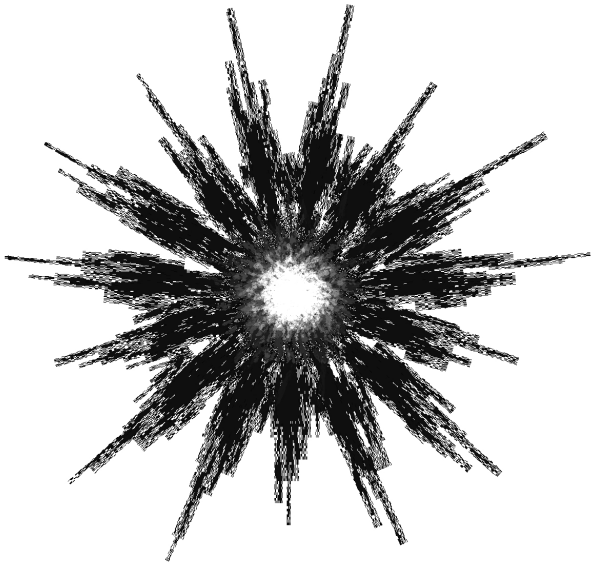
Integrated STAR

- Integration over multiple directions using MμSLIM



Integrated STAR

- Integration over multiple directions using MμSLIM



- Estimation of integrated PEA yields integrated STAR through ratio over TLA

Virtual experiment: Geometry

4 geometrical traits related were chosen

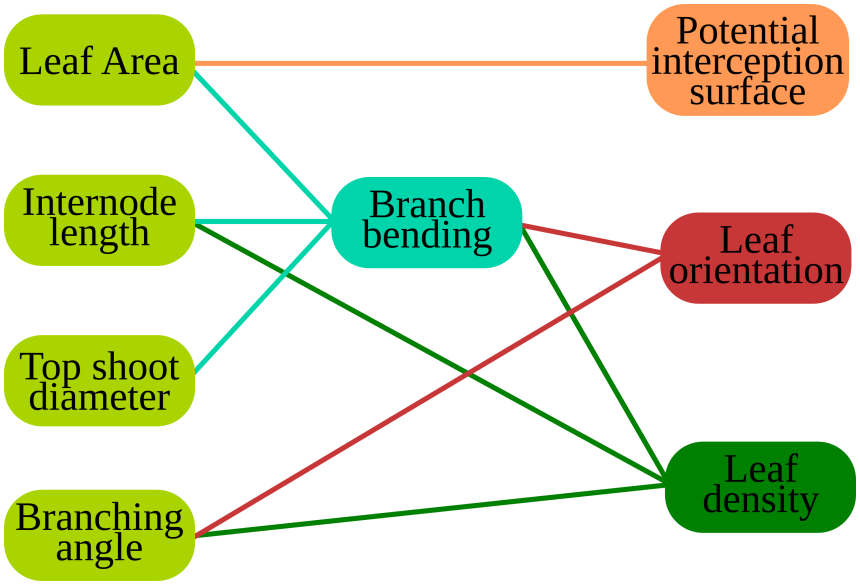
$LA \in [3.10^{-4}\ m^2 ; 9.10^{-3}\ m^2]$

$IL \in [8.10^{-3}\ m ; 5.10^{-2}\ m]$

$TSD \in [10^{-3}\ m ; 85.10^{-4}\ m]$

$BA \in [0\ ^o ; 130\ ^o]$

3 aspects may have direct influence on STAR



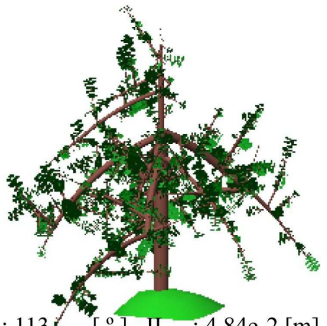
- Trees simulated over 5 years of growth
- STAR at tree scale estimated on 06/30 of each year

Virtual experiment: Geometry

BA : 96.7 [°] IL : 3.50e-2 [m]
TSD: 3.40e-3 [m] LA : 2.20e-3 [m²]

BA : 23.3 [°] IL : 1.61e-2 [m]
TSD: 6.98e-3 [m] LA : 2.18e-3 [m²]

BA : 122 [°] IL : 3.22e-2 [m]
TSD: 5.66e-3 [m] LA : 3.34e-3 [m²]

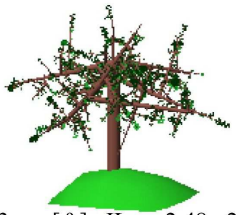


BA : 113 [°] IL : 4.84e-2 [m]
TSD: 7.67e-3 [m] LA : 2.24e-3 [m²]

BA : 101 [°] IL : 1.83e-2 [m]
TSD: 3.64e-3 [m] LA : 4.92e-3 [m²]

BA : 8.08 [°] IL : 4.86e-2 [m]
TSD: 3.18e-3 [m] LA : 1.48e-3 [m²]

BA : 36.4 [°] IL : 3.56e-2 [m]
TSD: 4.88e-3 [m] LA : 8.33e-3 [m²]

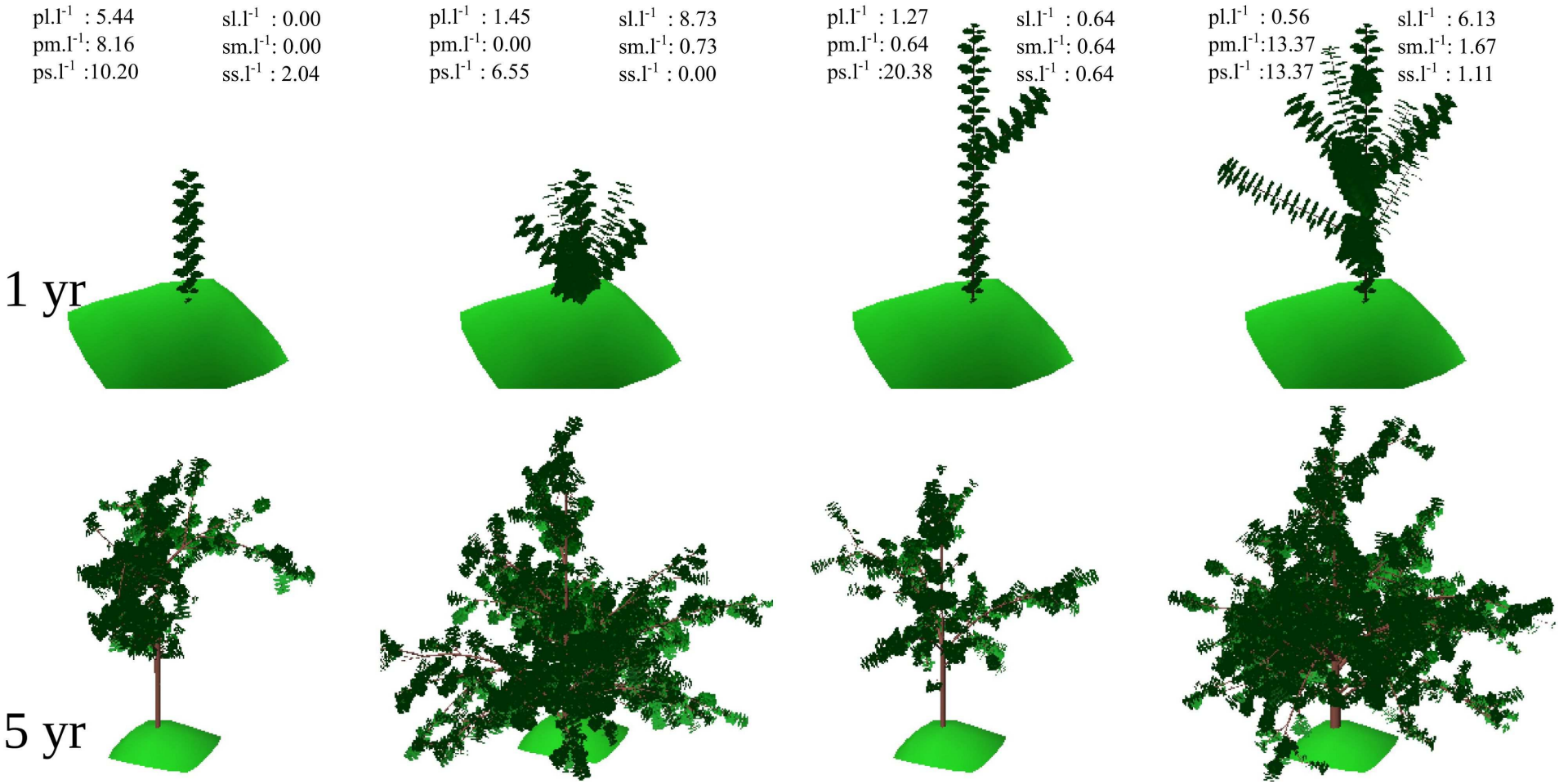


BA : 103 [°] IL : 2.48e-2 [m]
TSD: 4.76e-3 [m] LA : 3.08e-4 [m²]

Virtual experiment: Topology

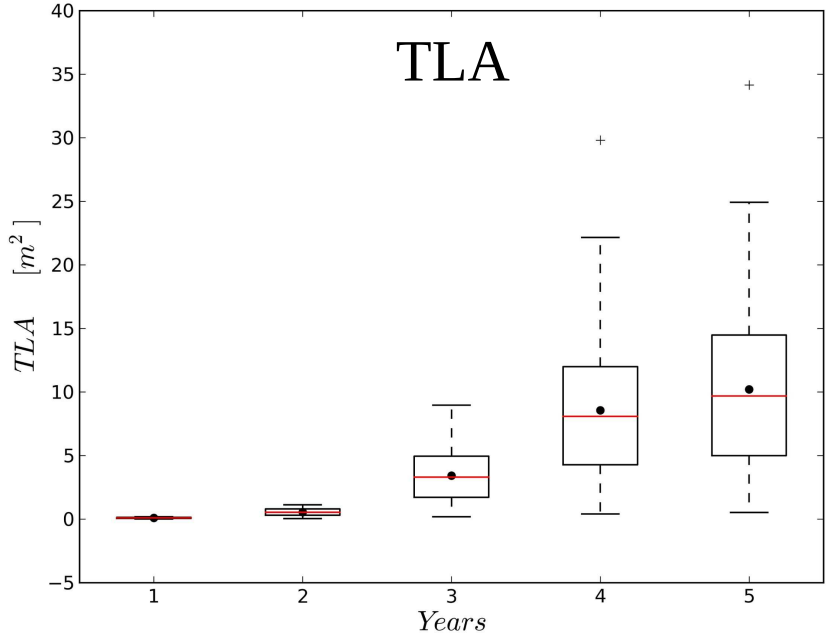
- Branching density was estimated as:
- For 6 different types of shoot
    - Sylleptic vs. proleptic
    - Long, medium and short sylleptic
- Trees simulated over 5 years of growth
- STAR at tree scale estimated on 06/30 of each year
- Computational time from 1 hour to 36 hours

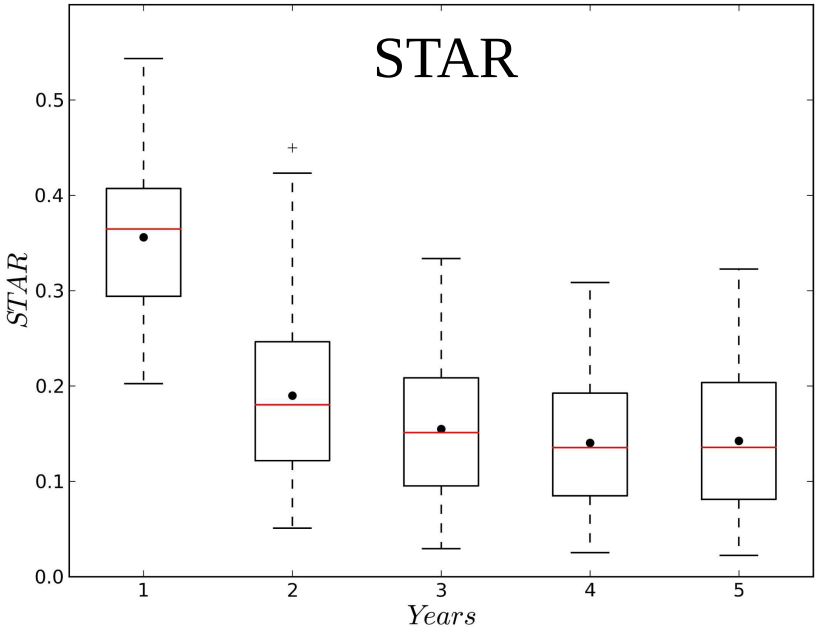
Virtual experiment: Topology



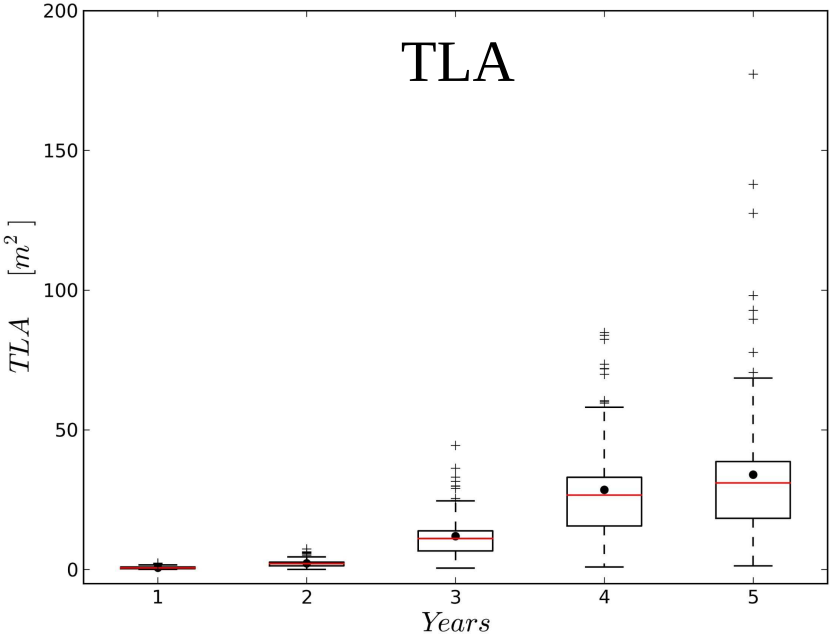
TLA and STAR evolution

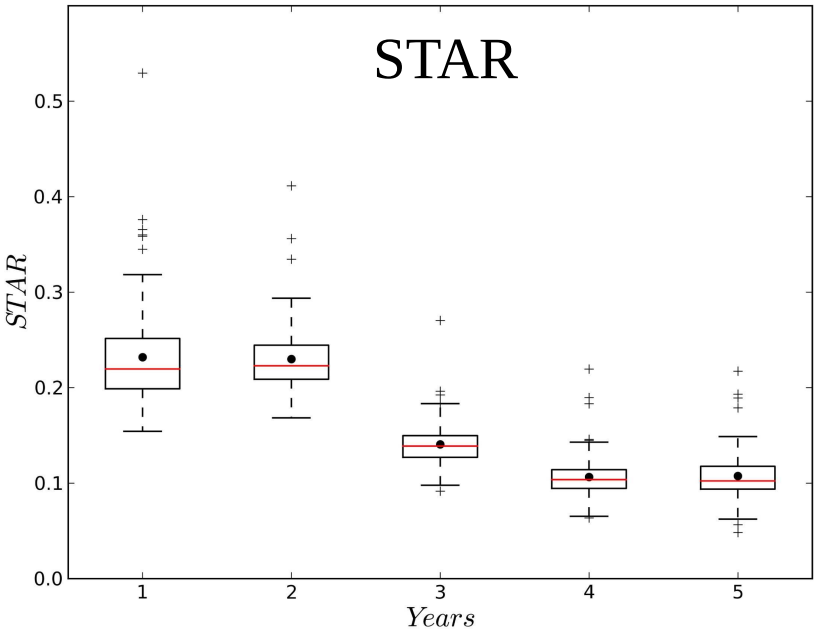
Geometry





Topology





Metamodelling approaches

- Generalized Additive Model (GAM) [Wood, 2006]
  - STAR as an additive sum of nonparametric functions

$$STAR_{i,k_1,\dots,k_p} = \sum_{j=1}^{p} f_{k_j}\left(X_{k_j,i}\right) + \epsilon_i$$

where k is one of the p parameters/factors in X for tree i ; ε is the residual error term

- Polynomial Linear MetaModel (PLMM) [Faivre, 2013]

$$STAR_{i,k_1,\dots,k_p} = \beta_0 + \sum_{l} \beta_l \Pi_{l_1,\dots,l_p} X_{k_j,i}^{j_l} + \epsilon_i$$

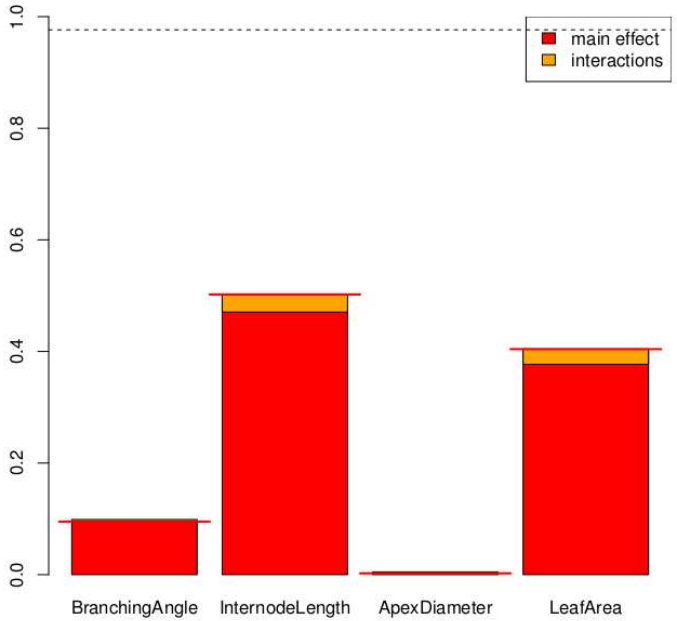
where $\sum j_l \leq d$; ε is the residual error term

Investigating model response: Geometry

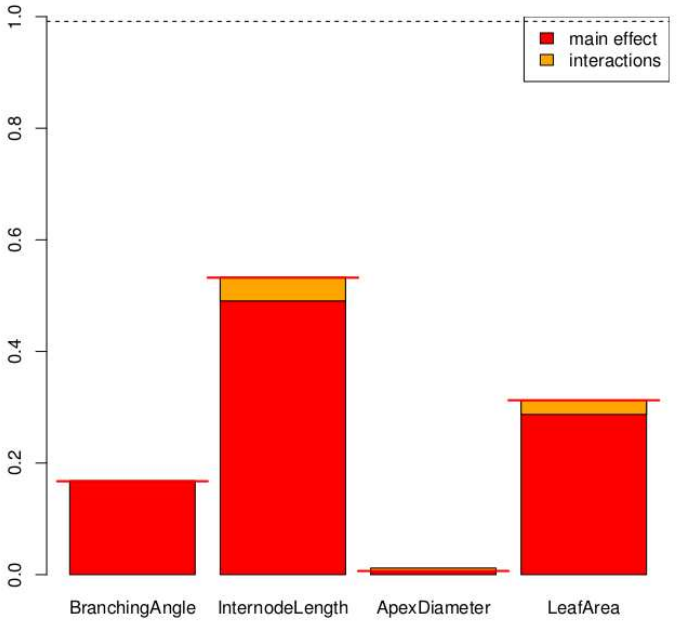
- Taille de l'échantillon : 300 + 300 (germe fixée)
- Temps d'une expérience numérique : 15 à 25 mn
- Plan d'expérience : LHS sur 4 facteurs
- Analyse sur 5 années de simulation
- Métamodèle : plmm + gam

Investigating model response: Gometry

Stochastique



Graine fixée

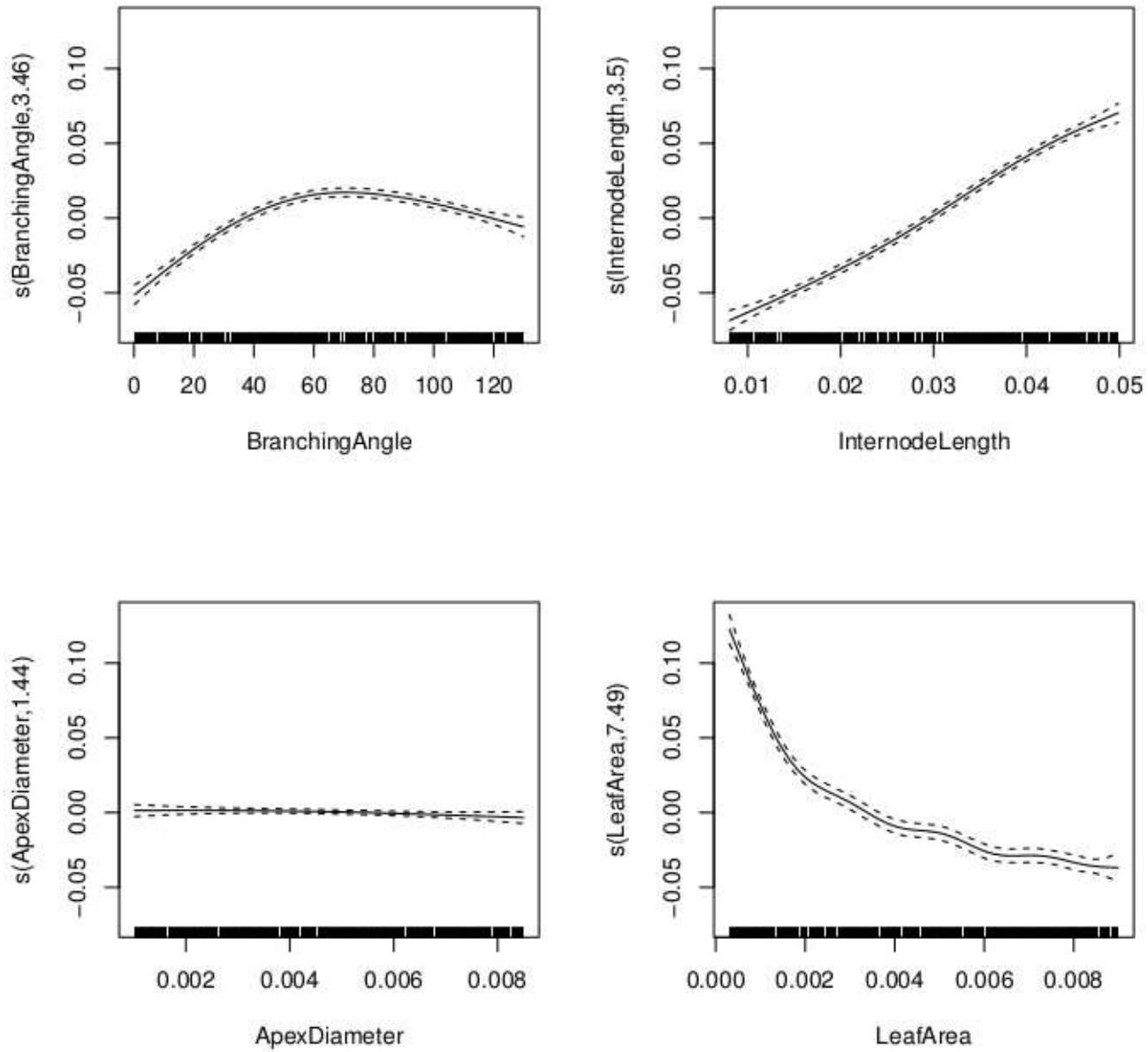


très peu d'interactions

Investigating model response: Gometry

Years		edf	F	p-value		R^2
1	BA	1	0.09	0.76		0.995
	IL	4.68	6089.98	<2e-16	***	
	TSD	1.34	19.72	1.65e-7	***	
	LA	7.33	2542.99	<2e-16	***	
2	BA	4.58	131.11	<2e-16	***	0.953
	IL	3.53	642.1	<2e-16	***	
	TSD	1.14	0.11	0.796		
	LA	6.68	267.05	<2e-16	***	
3	BA	4.18	142.82	<2e-16	***	0.955
	IL	2.25	1043.3	<2e-16	***	
	TSD	1.51	2.1	0.128		
	LA	7.26	268.37	<2e-16	***	
4	BA	3.7	92.86	<2e-16	***	0.946
	IL	3.23	595.94	<2e-16	***	
	TSD	1.35	0.81	0.425		
	LA	8.2	228.4	<2e-16	***	
5	BA	3.46	92.17	<2e-16	***	0.94
	IL	3.5	500.71	<2e-16	***	
	TSD	1.44	1.2	0.299		
	LA	7.49	207.19	<2e-16	***	

Investigating model response: Gometry



Investigating model response: Topology

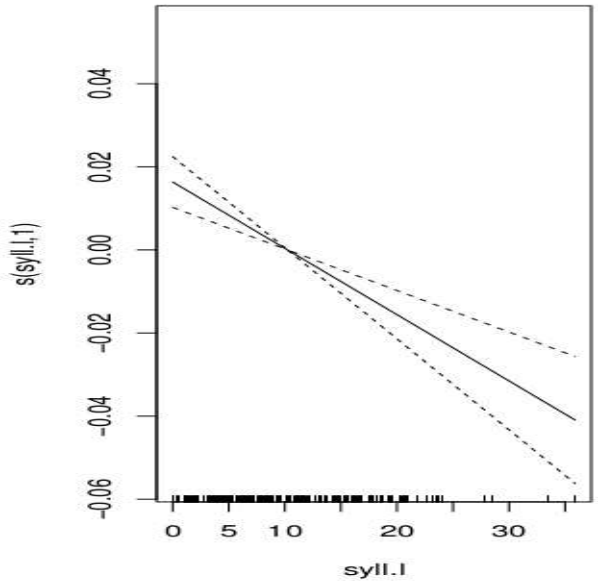
- Temps d'une expérience numérique : 15 à 25 mn
- Plan d'expérience : hybrides “réels”

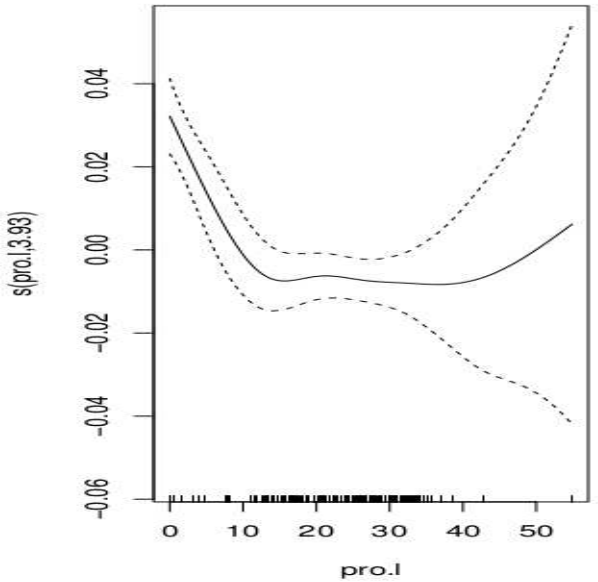
  densités des types de tige non contrôlées
- Taille de l'échantillon : 108
- Analyse sur 5 années de simulation
- Métamodèle : gam

Investigating model response: Topology

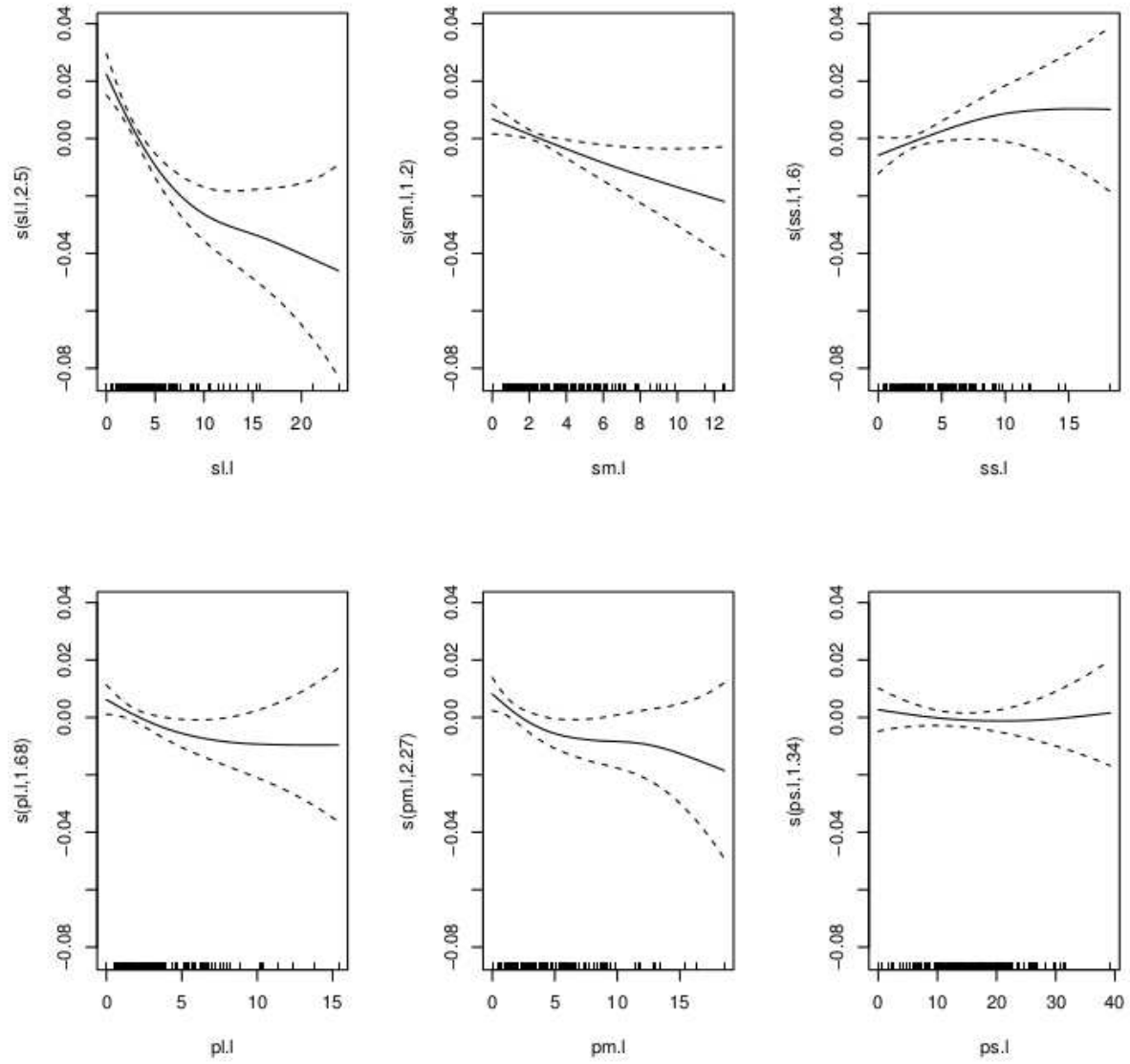
Years		edf	F	p.value		R^2	Years		edf	F	p-value		R^2
1	syll.l-1	3.23	38.04	<2e-16	***	0.6	1	sl.l-1	3.51	12.53	1.31e-08	***	0.58
	pro.l-1	2.98	1.73	0.15				sm.l-1	2.13	7.98	0.000168	***	
								ps.l-1	1.92	3.01	0.044906	*	
2	syll.l-1	1.05	35.38	2.17e-08	***	0.42	2	sl.l-1	2.34	16.85	8.87e-09	***	0.57
	pro.l-1	3.45	8.59	1.51e-05	***			sm.l-1	1.00	11.44	0.00104	**	
								pm.l-1	3.14	7.82	1.97e-05	***	
3	syll.l-1	2.44	3.09	2.05e-04	***	0.31	3	sl.l-1	2.15	20.61	1.4e-09	***	0.54
	pro.l-1	4.16	5.13	6.84e-04	***			pm.l-1	3.96	3.96	0.00307	**	
4	syll.l-1	2.27	2.870	2.26e-05	***	0.35	4	sl.l-1	2.20	20.32	8.54e-10	***	0.53
	pro.l-1	4.58	5.612	2.37e-04	***			pm.l-1	3.99	3.06	0.0138	*	
5	syll.l-1	2.05	2.593	1.57e-05	***	0.31	5	sl.l-1	1.90	21.32	2.22e-09	***	0.42
	pro.l-1	4.17	5.142	1.69e-03	**			pm.l-1	1.37	3.63	0.0386	*	

Investigating model response: Topology





Investigating model response: Topology



Conclusion and prospects: MappleT

- The internode length and leaf area had the highest impact on STAR
- Early branching showed lower impact on STAR than varying organ geometry.
- Increase in TLA through ramification exhibited a threshold of light interception efficiency.
- Long sylleptic shoots had a more significant effect than proleptic shoots
- Breeding and genetic selection could be a promising venue for saving time, labour and ressources, but some trait combination could be unrealistic

Conclusion et perspectives: Analyses

Sur l'étude Géométrie, on peut contrôler le plan

- Effet de la stochasticité compensé (adaptation du modèle)
- Métamodèles très explicatifs
- Métamodèle plmm ne note que très peu d'interaction
- Métamodèle gam détecte les non-linéarités

Sur l'étude Topologie, on est très contraint (facteurs d'analyse corrélés)

- Métamodèle plmm non envisageable, gam sans interaction (taille limitée)
- Autres : dynamique de classifications (typologie stable ?)

Ouverture sur optimisation (présentation de Victor, demain)

- Autre forme de métamodèle (processus gaussien)

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