3D and 4D forest models

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Finnish Centre of Excellence in Inverse Problems Research

Change of (information) paradigm in forestry

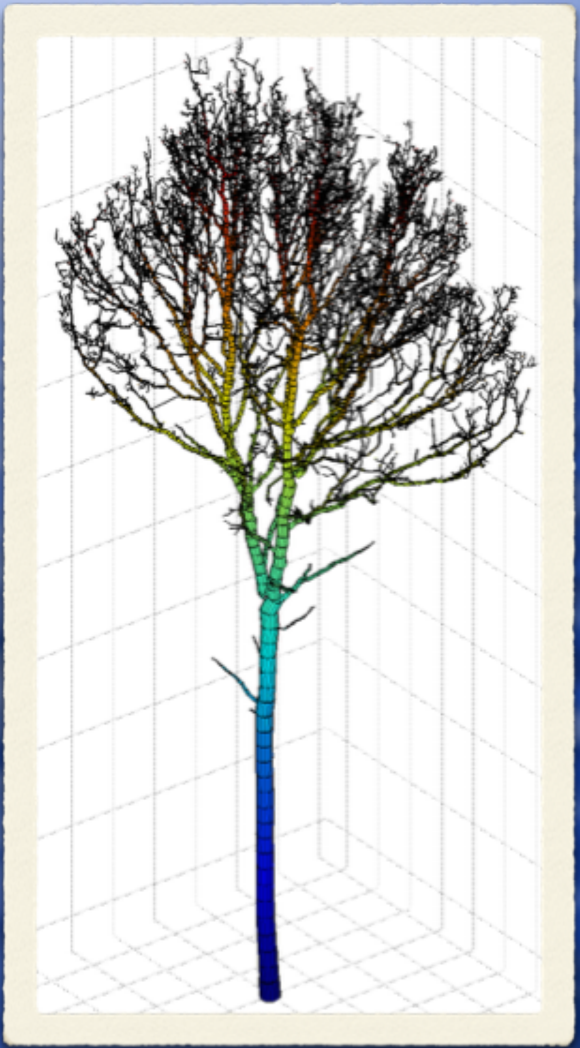
- New demands for modern ecosystem services: biomass quantity and distribution, carbon cycle and footprint, timber quality and market, cultivation options, ecological and recreational functions, urban areas, …
- Full forest information: “Google Nature” in your mobile phone
- 3D models, 4D time development
- Complete virtual environment: view from any location
- Quantitative: obtain any volumetric or geometric numerical results from any region
- Predictive: how will trees grow in different scenarios?

Smart forest and infosphere

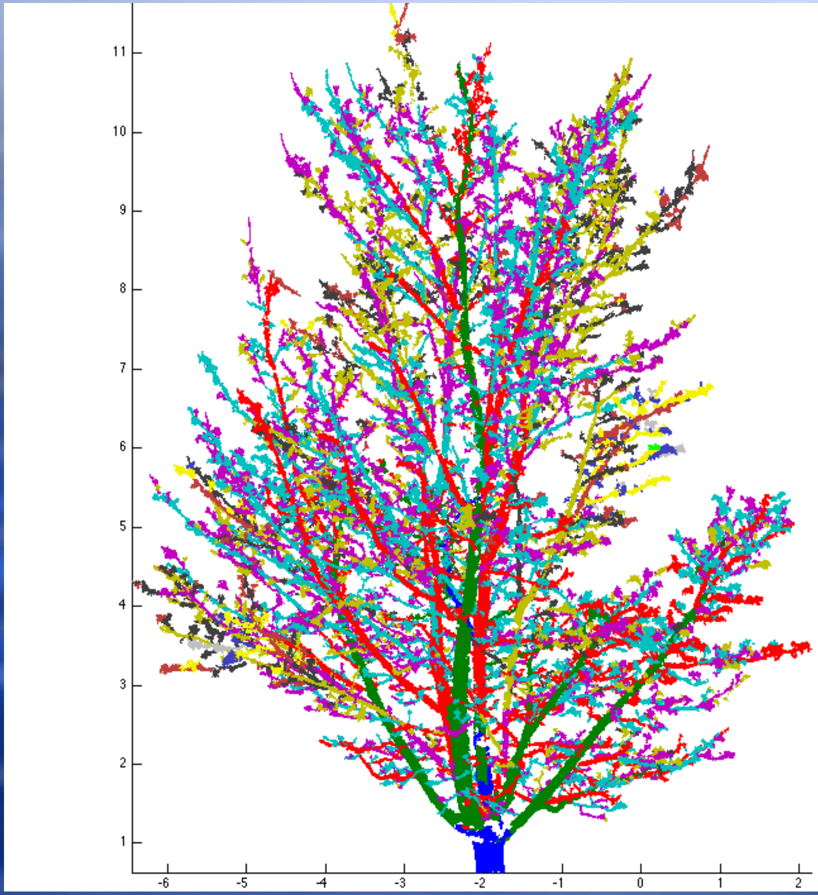
- See it, scan it, handle it with quantitative structure models (QSMs)
- Can do, will do: crowdsourcing – mobile lidar for everyone
- Upscaling: from terrestrial laser scanning (TLS) to satellite data – large comprehensively analyzed test plots for large-scale calibration
- Hyperspectral lidar information
- Represent leaves as “gas” or stochastic primitives around branches with matching leaf area density etc.

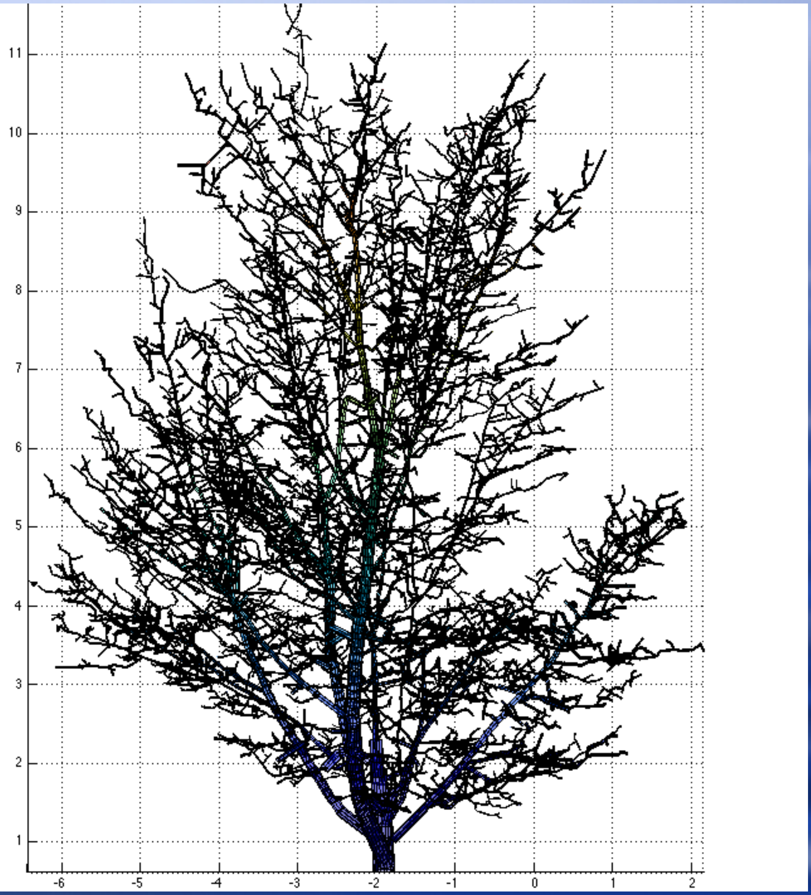
QSM - Quantitative Structure Model

* Compact tree model containing essential topological and geometrical tree properties
  * Branching structure, branching order
  * Volumes, lengths, angles, taper, etc.
  * Rapid advances in laser scanning technology: lighter, cheaper, faster
  * => Ubiquitous laser scanning (cf. radars in cars)



Compact usable information



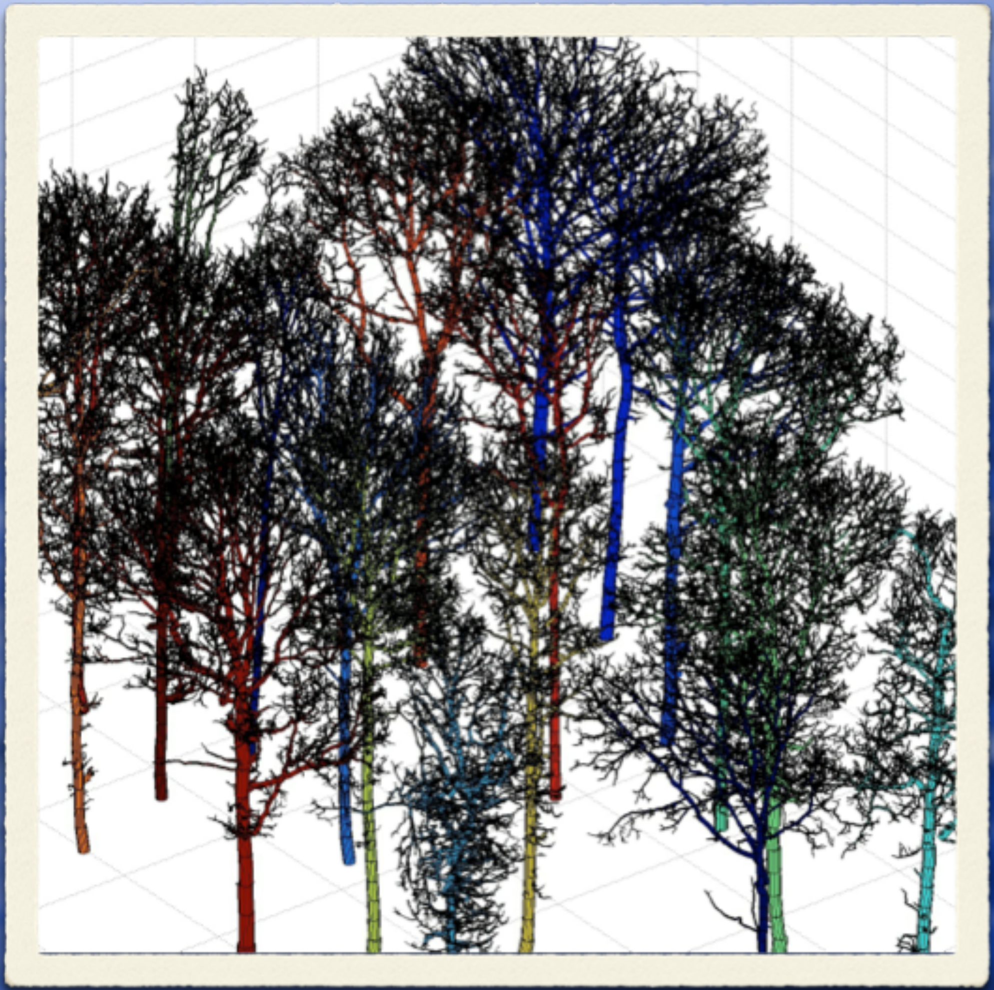


3 scan positions, high resolution (1,6M points)

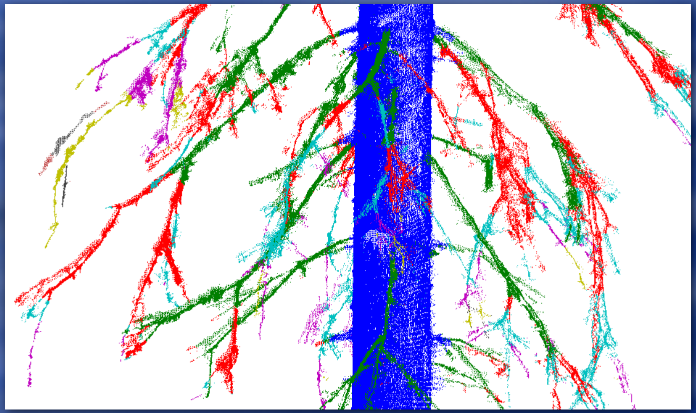
Model (14 000 cylinders)

Forest plot QSMs

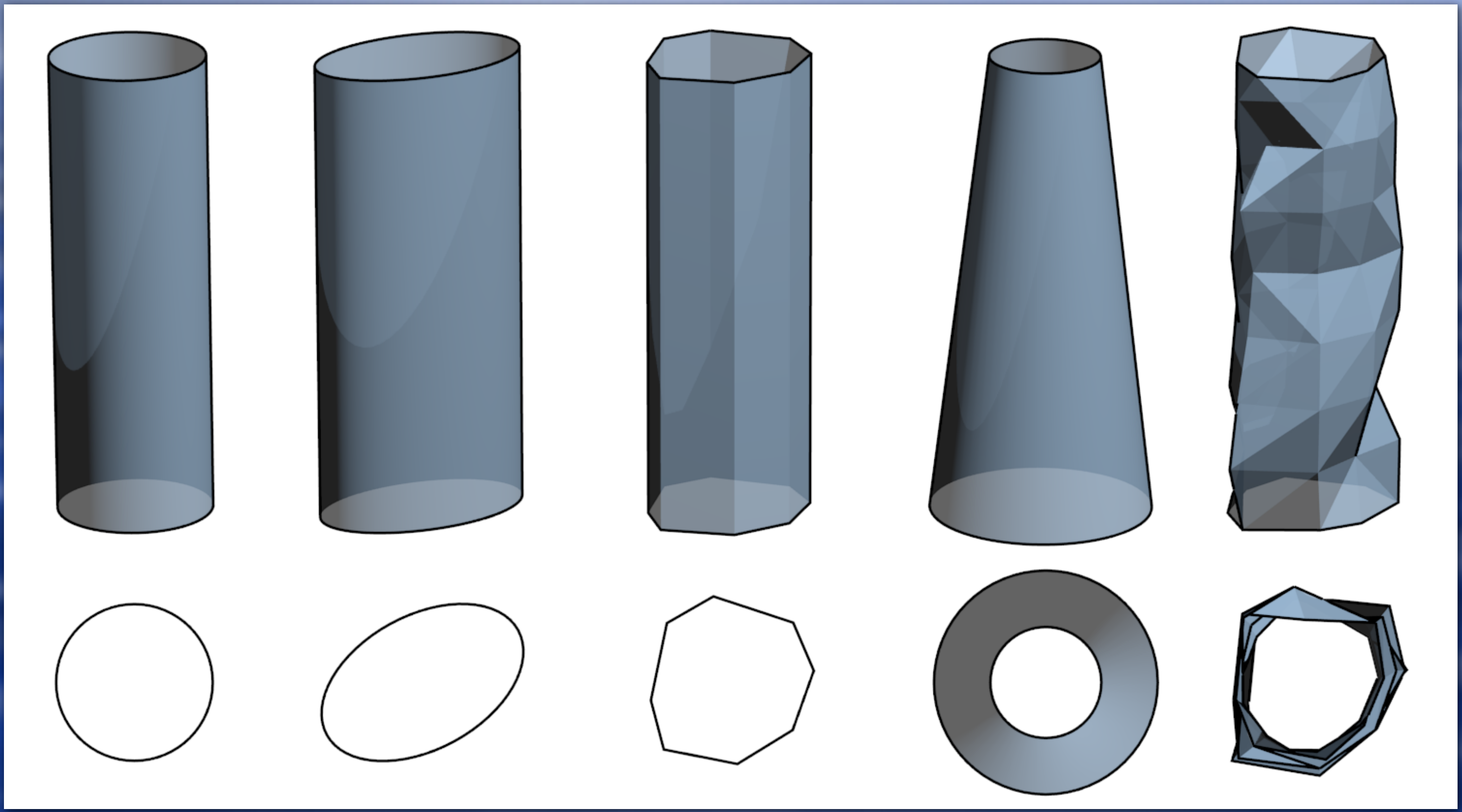
- Fast modelling, tens of big trees in an hour
- Parallel computing allows hundreds of big trees in an hour
- Use the smallest required surface patch size instead of all points
- Robust cylinders as geometric primitives
- Surface continuity not required



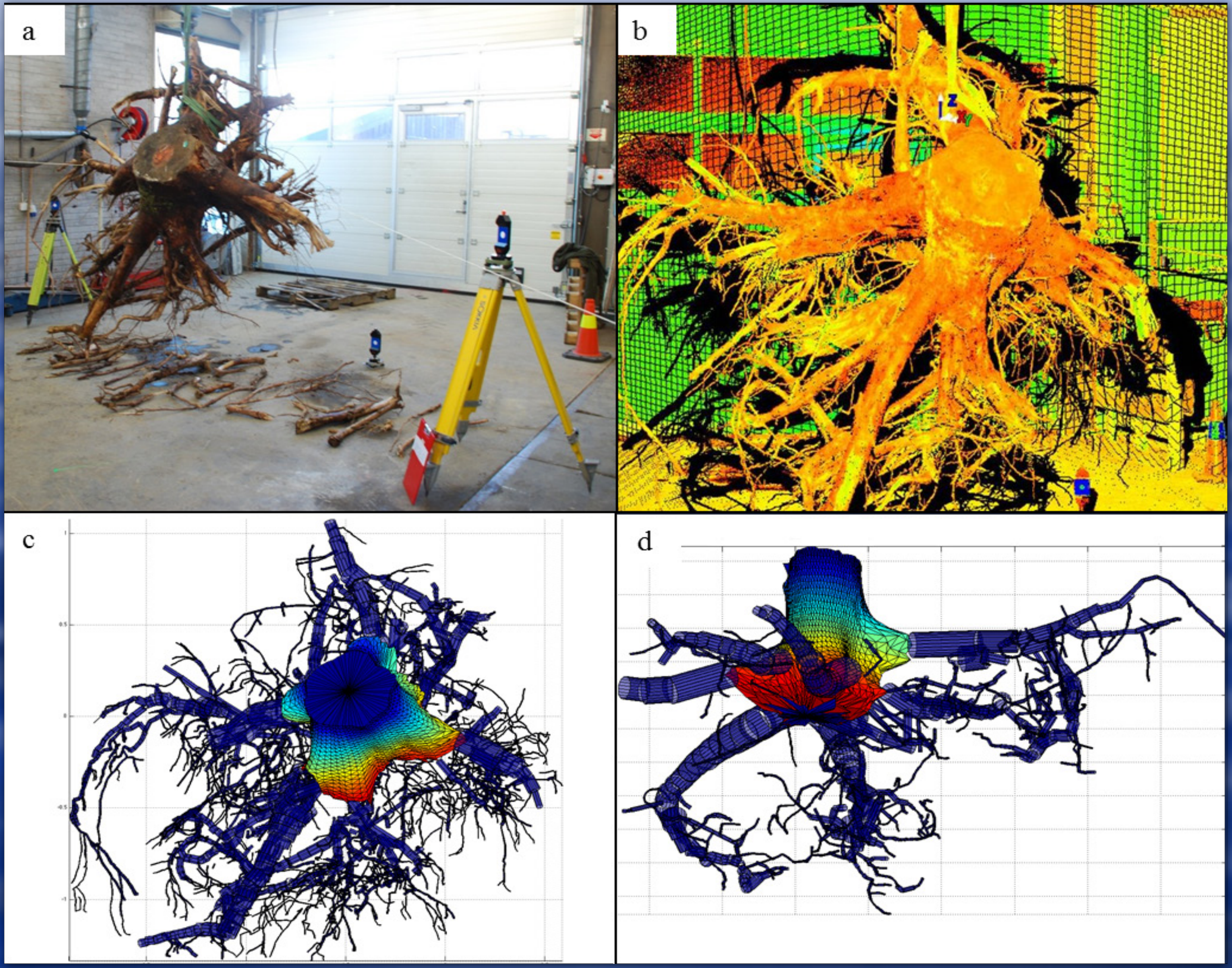
Cover sets and segments



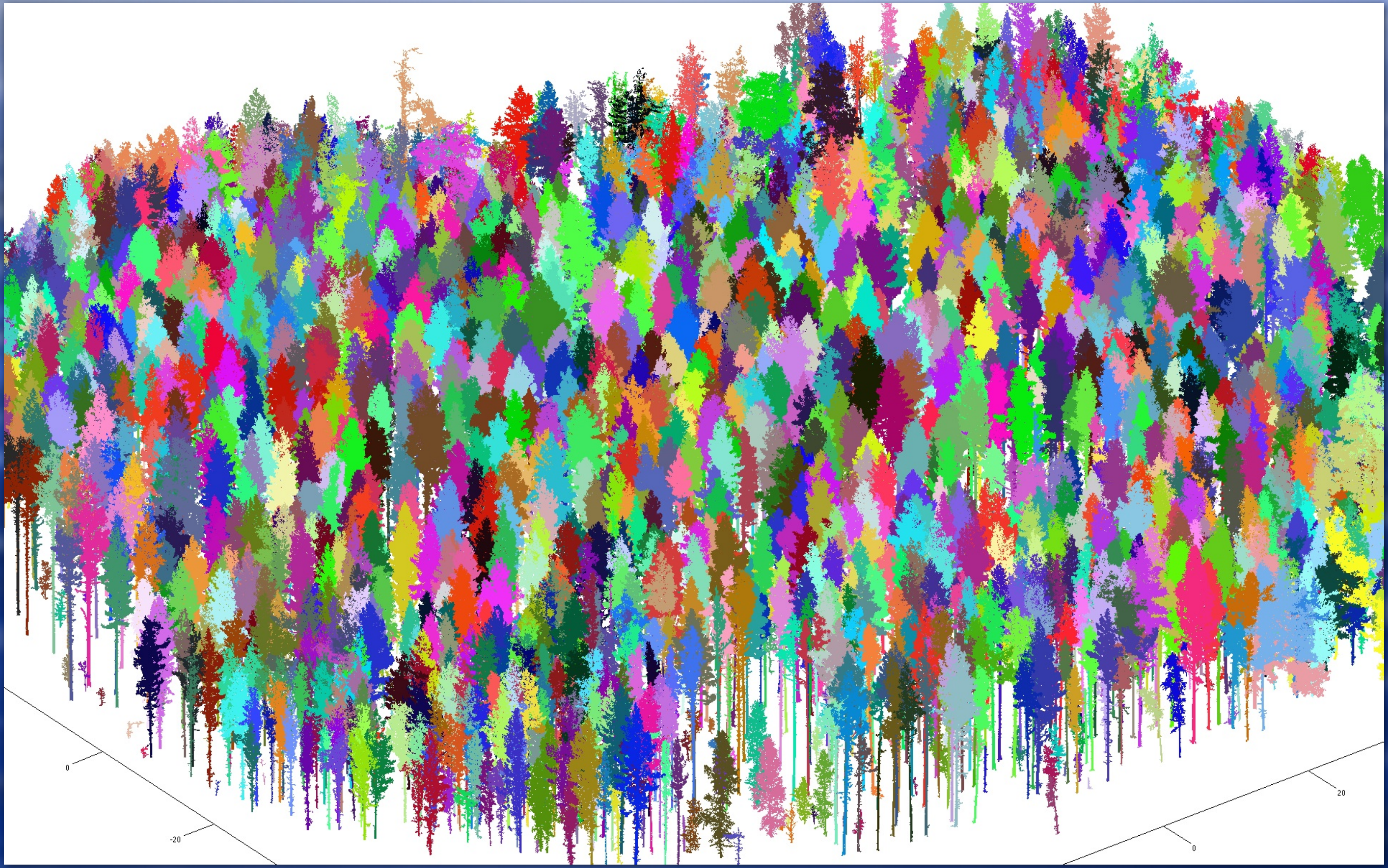
Other geometric forms



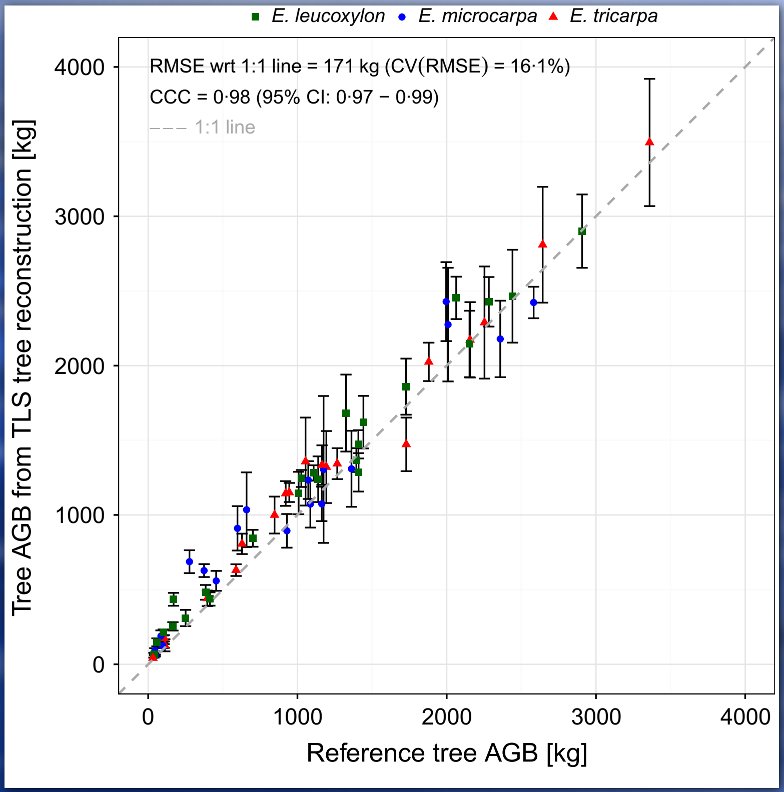
Complex shapes possible

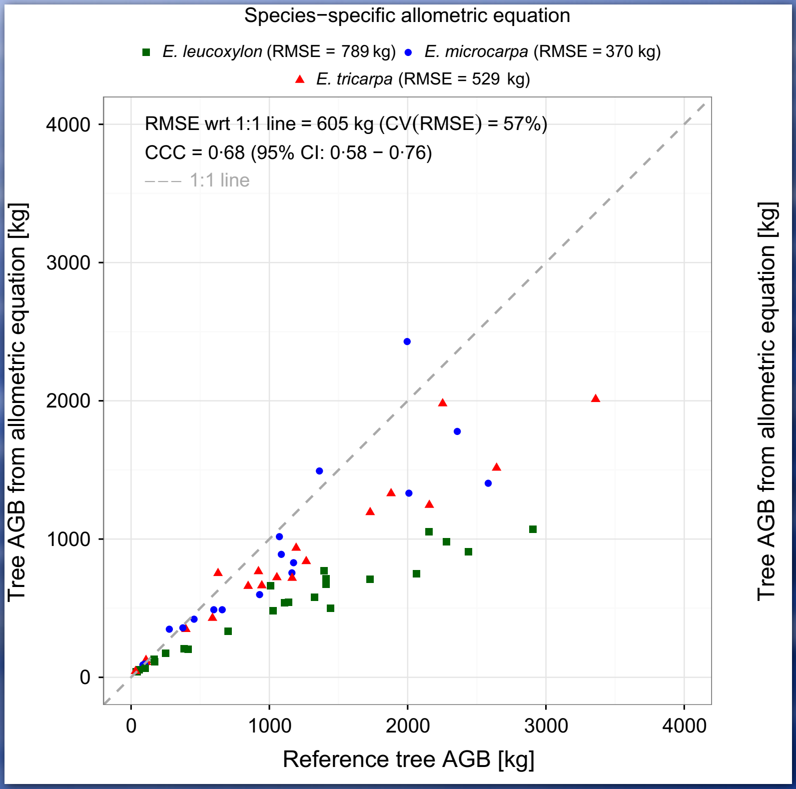


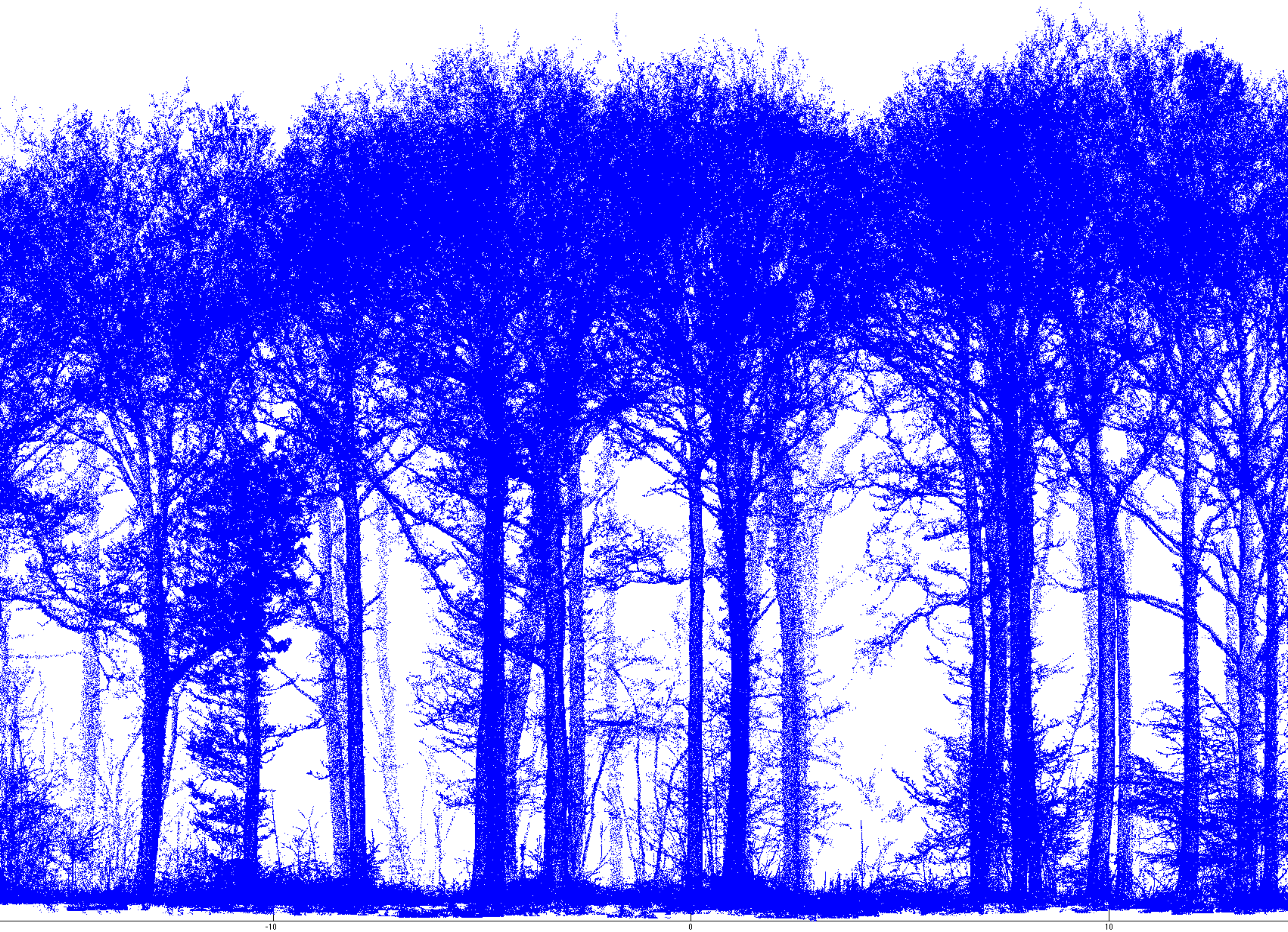
A day's work (scan from 10 spots, QSM on laptop)

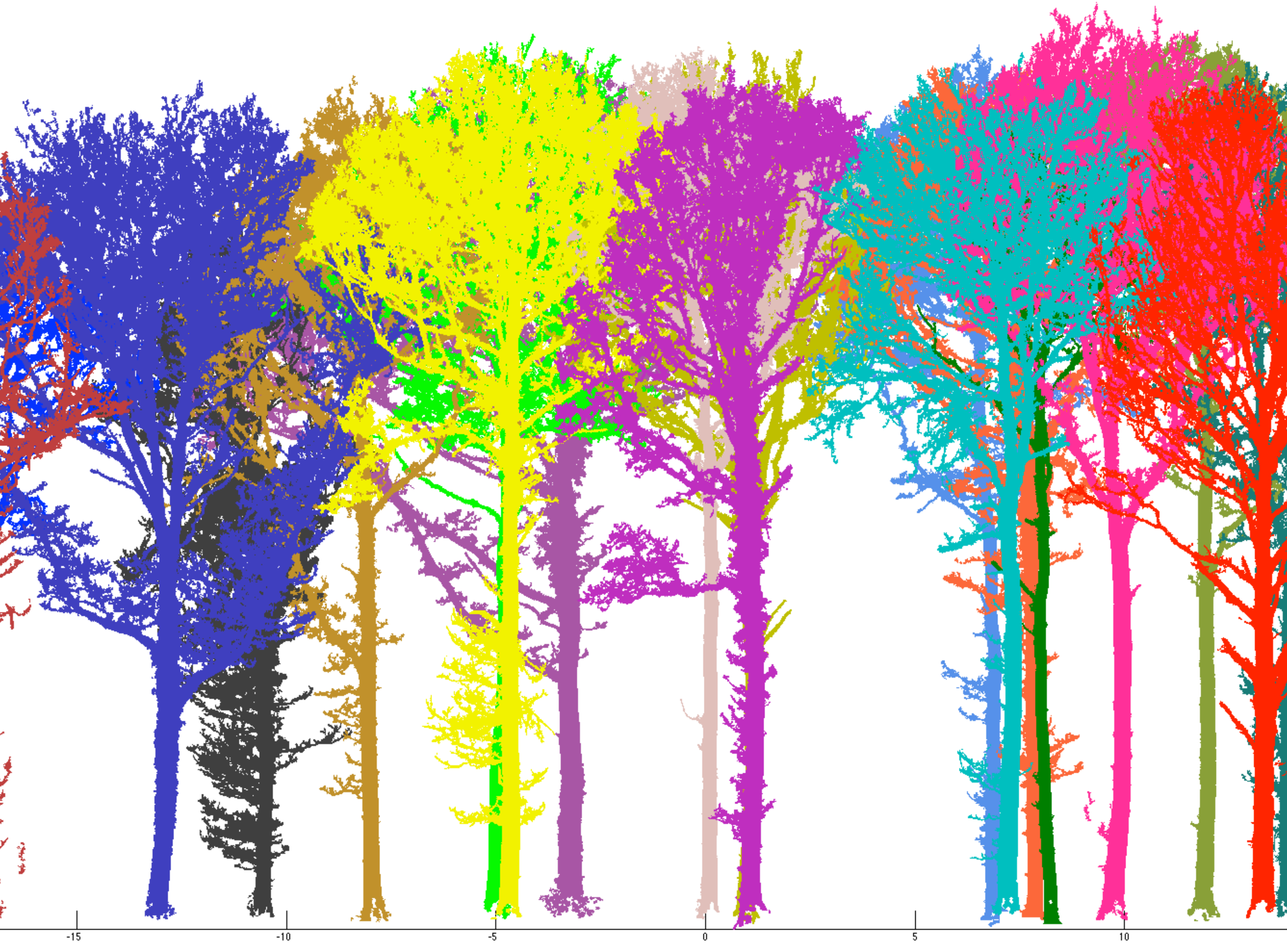


QSM vs. allometry: Australian Eucalypt plot (109 trees)






-10
0
10



-15
-10
-5
0
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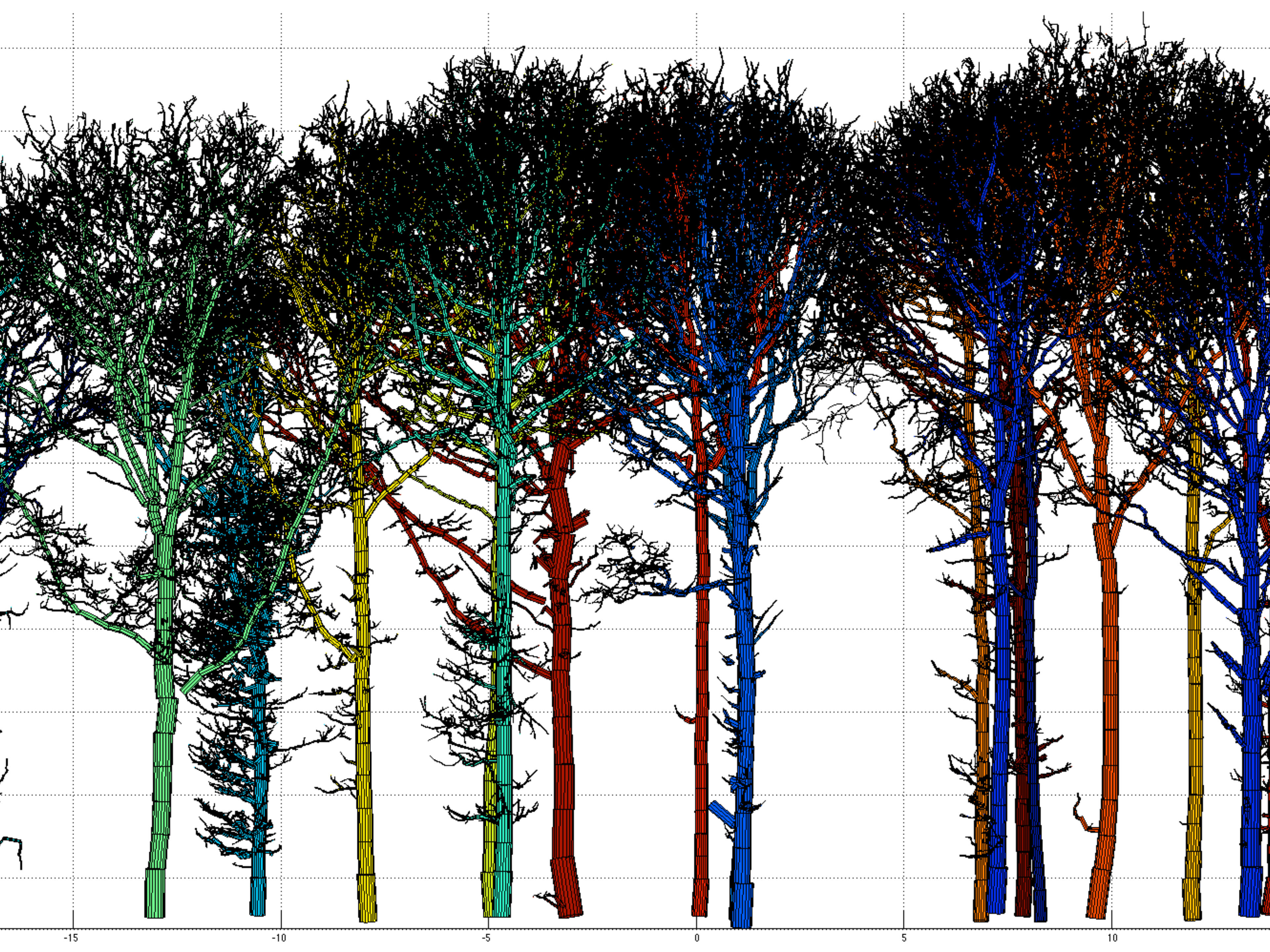

-15
-10
-5
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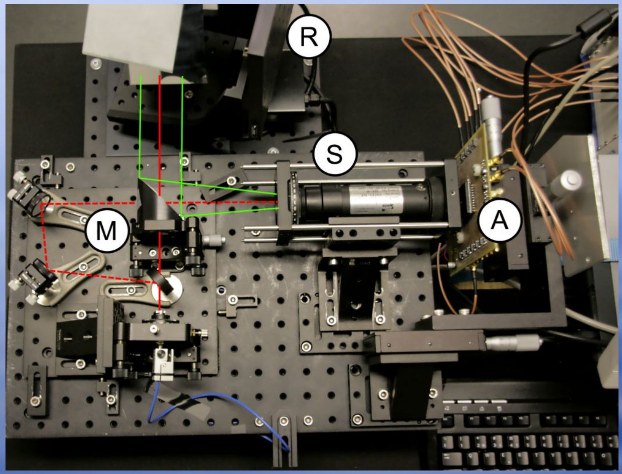
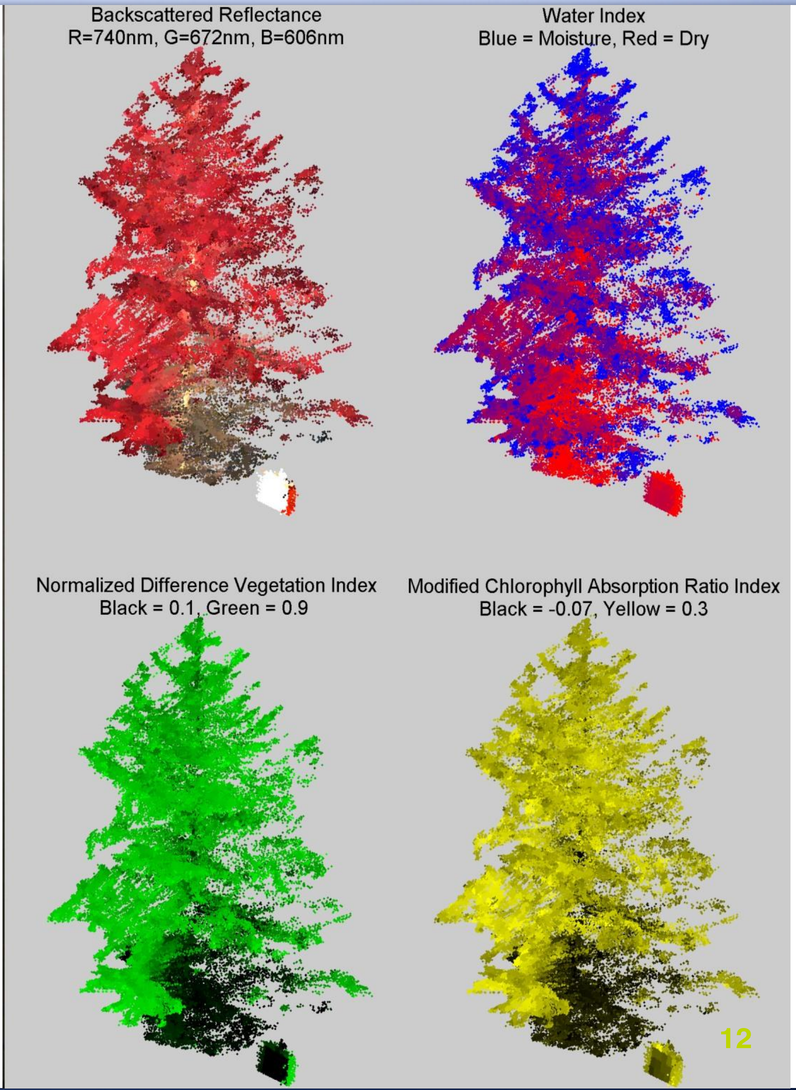
The FGI hyperspectral lidar

- New concept & technology in laser scanning
- Active hyperspectral imaging simultaneously with topographic information
- Spectrum directly available for each point
- Based on supercontinuum laser technology



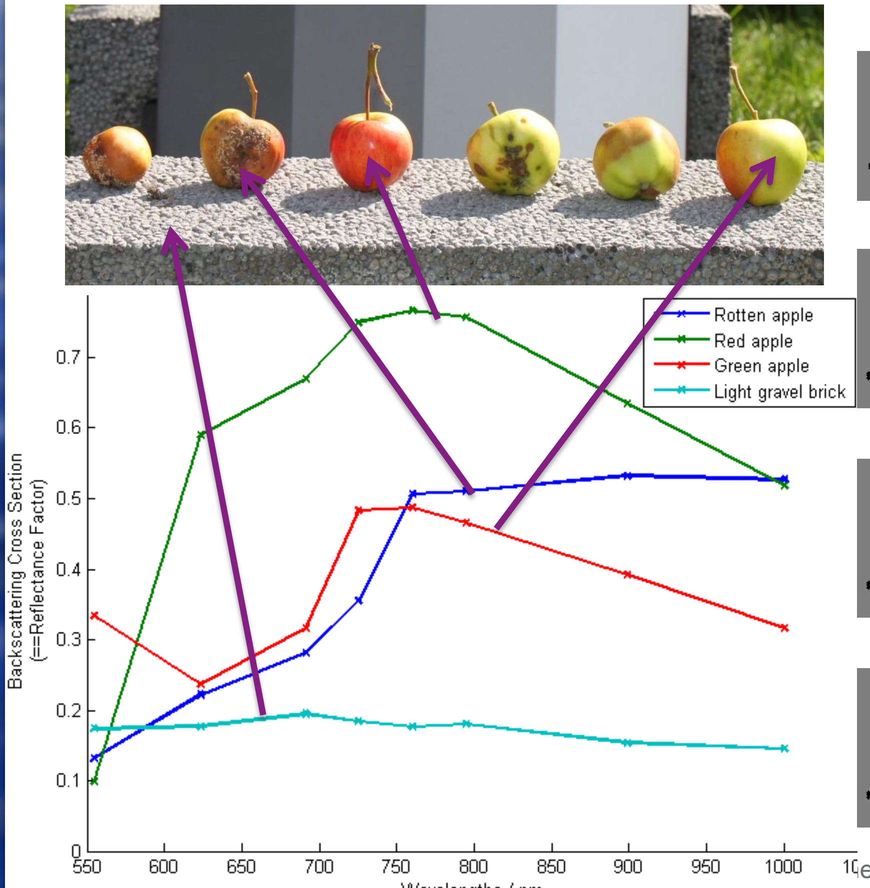
Hyperspectral lidar (HSL)

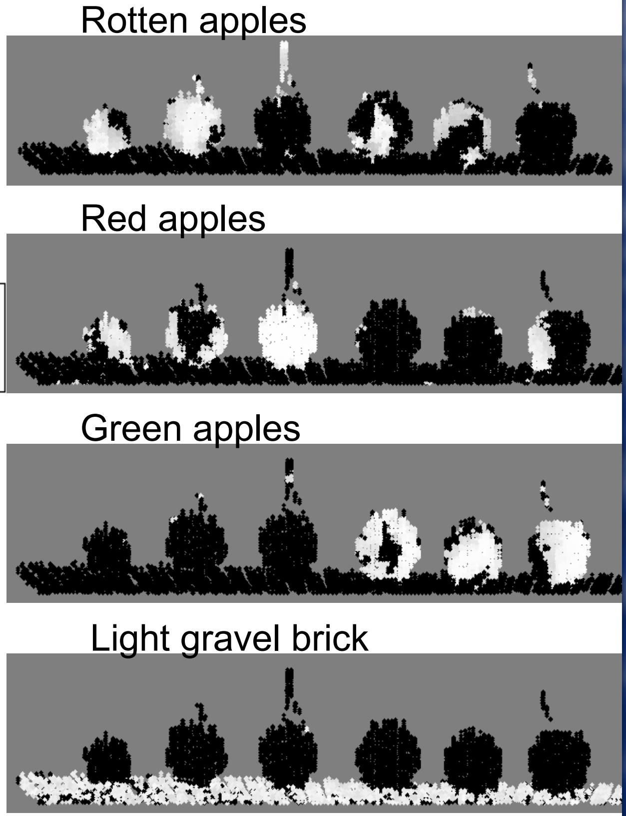
Applications



HSL: target recognition

Target classification example

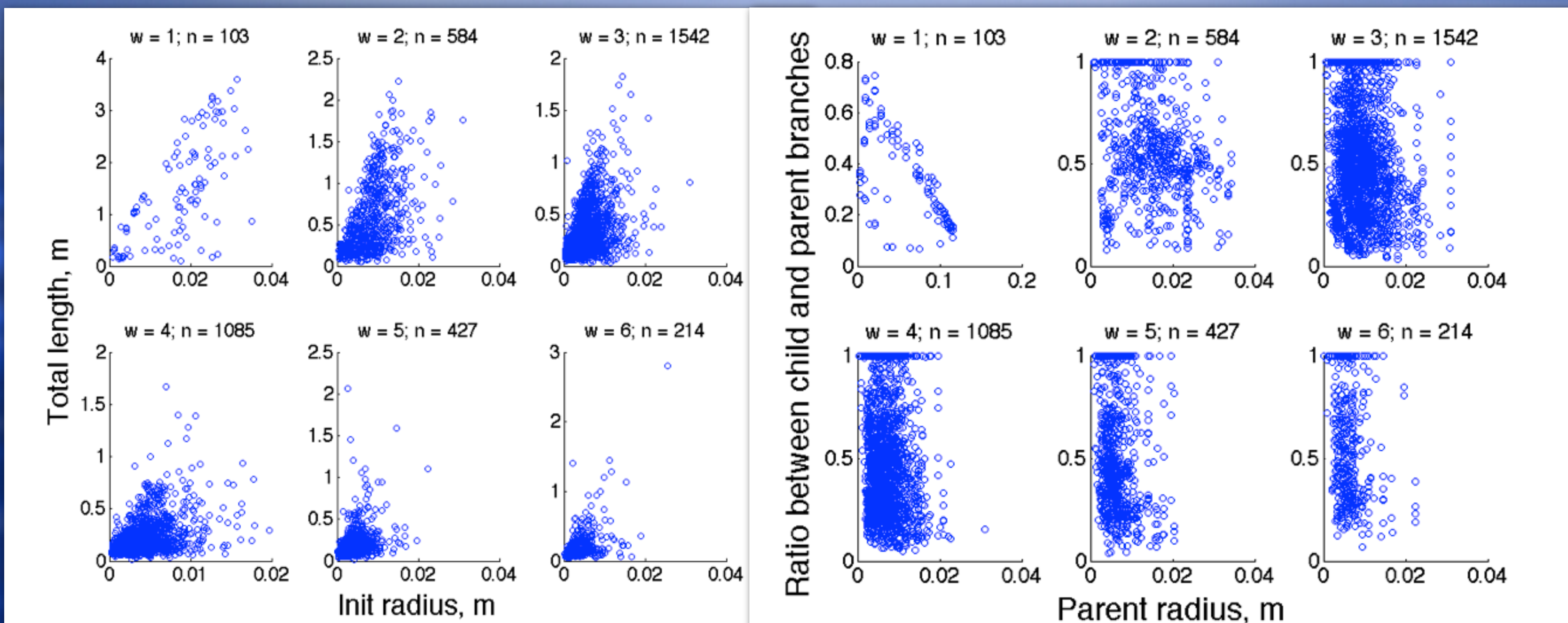




Trees and forests as probabilistic concepts

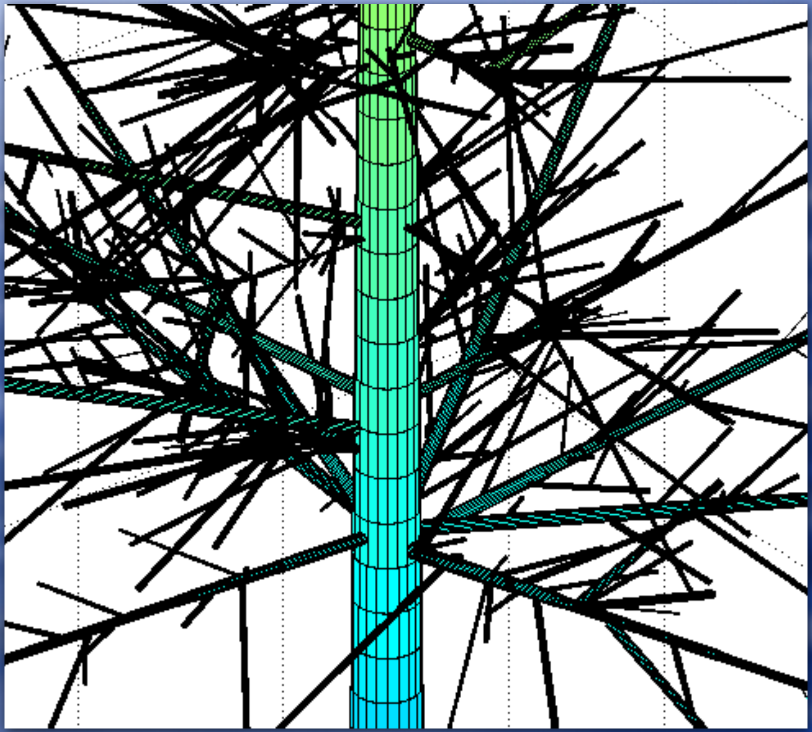
- The growth of a tree (forest, organism, branching system) is a stochastic process -- not random, but unpredictable to some degree: genotype+environment
- A structure snapshot of the tree/forest (at any time) is the result of this process that contains deterministic, self-organizing and constraining elements (e.g., two branches cannot occupy the same volume; the competition for light and resources)
- The structure data are distribution functions $p(u)$ in some measurement space spanned by u
- The growth process rules $q(s)$ of a tree model are also probability distributions (DFs): how likely is a tree to make a given choice (in some s-space) at a given time?

Sample distributions *p(u)*



4D tree growth

- HYPOTHESIS: the genotype of a tree and environmental constraints can be represented by low-dim. stochastic DFs *q(s)*
- This handles competition and other development effects in a consistent manner, and reduces the problem dimension
- 4D measurement data and fitting *q(s)->p(u)* to 3D-data *u*-point distributions: likelihood-free inference
- Applicable to other organisms, societies, cities: find the growth rules



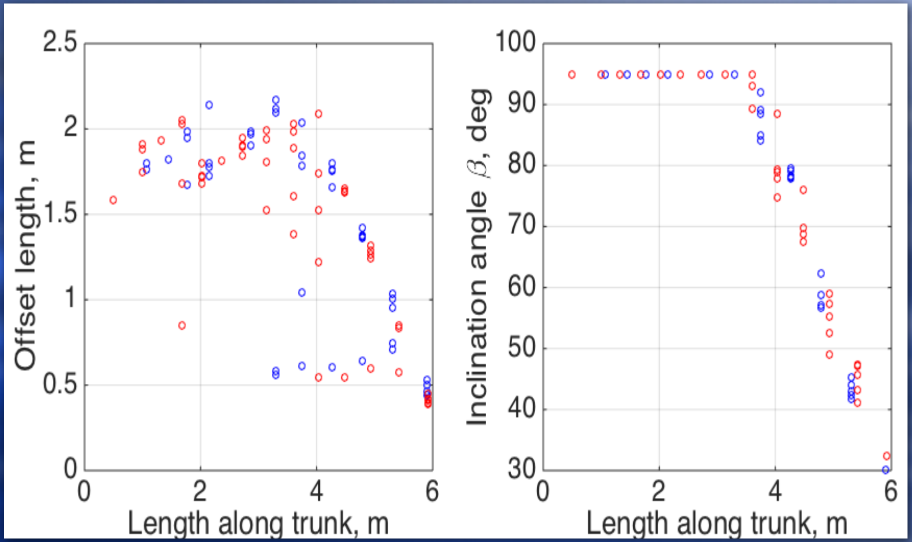
FSPMs and synthetic trees

- We can use biology-based theoretical functional-structural plant models (FSPMs) such as Lignum, or
- More fully synthetic "4D-geometric" models that flexibly represent "typical" aspects of growth and structure without actual biological rules;
- Any practical model has elements of both; these are augmented with stochastic properties
- Deterministic parameters are turned into samples of DFs $q(s)$, and the parameters defining q are now our new model parameters
- With such a tuned model, we can create statistically similar trees that are not clones

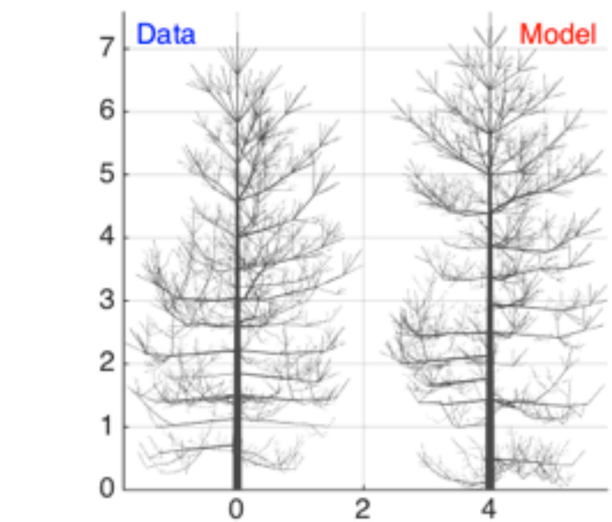
Structure distance measure

- Once we have a stochastic model with a parameter set, we create several sample trees from *q(s)* out of which we create QSMs and thus *p(u)* in selected spaces
- We define the structure distance measure; i.e., the difference *D* between two *p(u)* -- in principle zero for stat. similar trees of the same *q(s)*
- Then we minimize $D[p(u)_{\text{data}}, p(u)_{\text{model}}]$ iteratively (e.g., genetic algorithms) by tuning the parameters of *q(s)*
- There is no unique choice for the model, *D*, *s*, or *u*, or the parametrization of *q* and *p* (e.g., Gaussian)
- The choices probably depend on the species; we just have to experiment a lot
- Sometimes part of *q* and *p* may be essentially the same thing (e.g., distribution of branch tapering) so we get that part of *q* directly

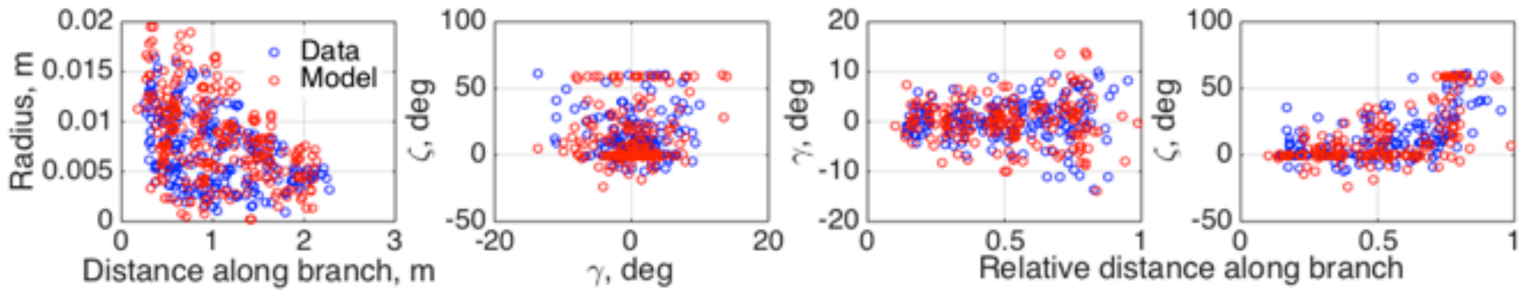
Lignum simulation



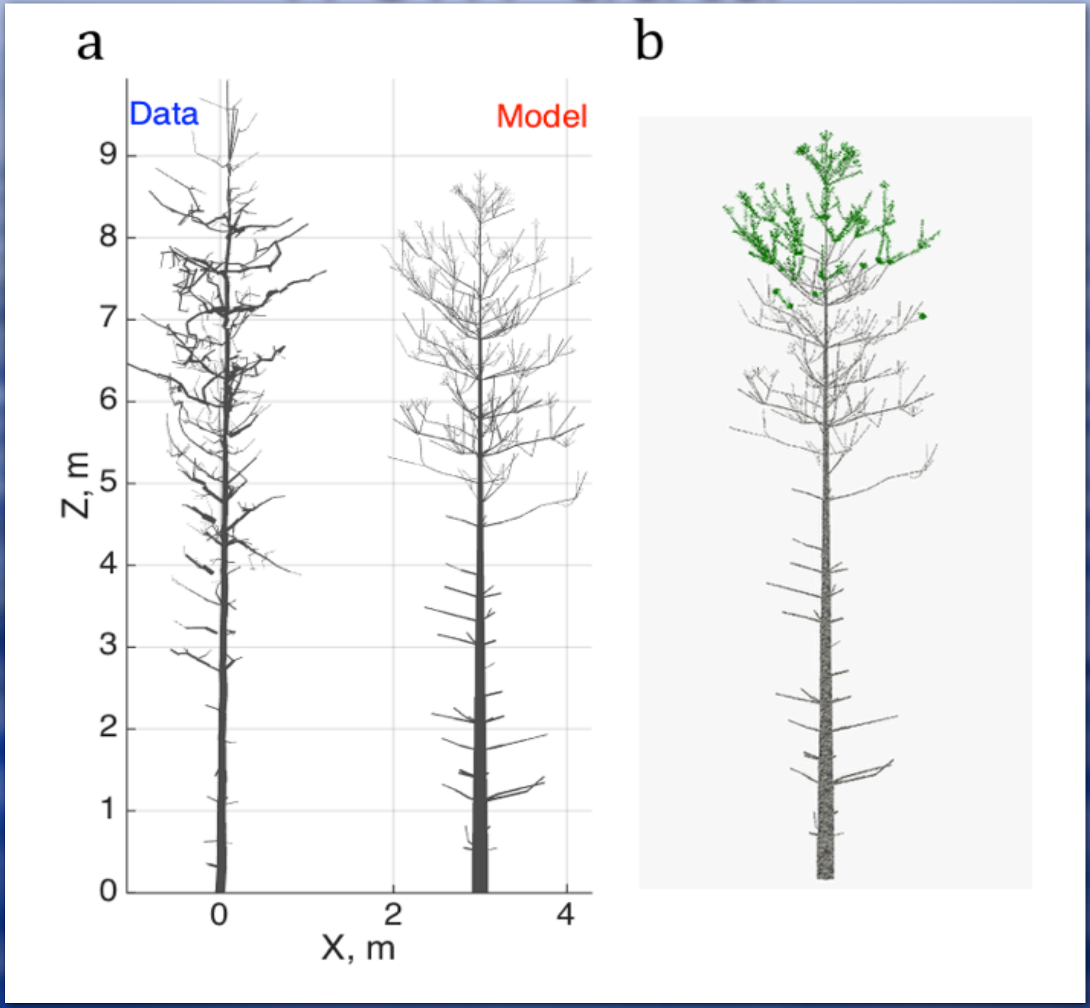
Lignum simulation



Parameter name	Data value	Model value (estimated)	Relative error, %
L_R, mean	0.009	0.0094	4.65
L_R, std	0.001	0.0009	6.95
Q, mean	0.2	0.2058	2.88
Q, std	0.03	0.0213	28.88
T	15	16	6.67
$\Delta\beta$	10.0	9.7665	2.33
$\Delta\zeta$	5.0	4.3708	12.58
β_{init}	35.0	40.4649	15.61



Stochastic augmented Lignum from data



Literature

- Raumonen & al. 2013, Rem. Sens. 5, 491
- Calders & al. 2015, Meth. Ecol. Evol. 6, 198
- Kaasalainen & al. 2014, Rem. Sens. 6, 3906

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