Digital reconstruction of tree architecture as a tool for assessing growth and functional performance

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Introduction

The topological and geometrical structure of crown, stem and root systems of trees is the result of growth and external factors. At the same time, this structure sets important boundary conditions for processes influencing further growth (e.g., PAR interception, xylem sap flow). Therefore, simulation models taking into account the 3-D tree architecture can help to check hypotheses about structural-functional relations affecting tree growth. However, to be of value, such models have to be based upon botanical knowledge and upon appropriate 3-D field data.

Measuring and encoding tree architecture

With manual and semi-automatic measurement techniques (digital compass), we obtained morphometric data from young Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) and oak (*Quercus petraea* (Matt.) Liebl.). The level of resolution was that of growth units (in most cases identical with annual shoots). Data were encoded in *dtd* format (Kurth 1994, 1999; example: Figure 1), suitable for exact 3-D reconstruction of the branched tree architecture with the software GROGRA (Kurth 1994). Leaf parameters (area, dry mass) were obtained at sample shoots (in some cases even at all shoots), and this information was linked with the architectural data.

The technique was first applied above-ground (Kurth & Anzola Jürgenson 1997, Kurth 1999), but later also to some excavated root systems (Oppelt et al. 2000a,b). Fig. 2 and 3 show reconstructed, virtual oak trees obtained this way.

```
33  L55   #32  V          D5.0      C6
34  L53   #33  V          D4.2      C6
35  L112  #34  V          D3.4         N0.14 P0.55
36  L125  #35  V          D3.1         N1.21 P0.33
37  L54   #36  V          D1.8         N0.19 P0.21
38  L61   #32      R5 W80 D1.8      C6
39  L75   #38  V   R3 W80 D1.2      C1
40  L65   #32      R7 W85 D3.3      C6
41  L61   #40  V          D2.8      C6
42  L83   #41  V          D2.5         N0.07 P0.21
43  L64   #42  V          D1.8         N0.05 P0.10
44  L29   #43  V          D1.7         N0.42 P0.09
45  L73   #40      R7 W70 D1.5         N0.22 P0.11
46  L81   #41      R7 W45 D1.5         N0.34 P0.14
47  L59   #42      R8 W75 D2.2         N0.36 P0.12
47a L41   #47  V          D1.8         N0.05 P0.09
48  L104  #34      R7 W45 D2.1         N0.46 P0.22
49  L38   #48  V          D1.0         N0.08 P0.01
50  L10   #48      R3 W110 D1.7        N0.23 P0.10
51  L25   #35      R7 W85 D0.9         N0.12 P0.12
52  L140  #35      R5 W35 D2.5         N1.13 P0.30
53  L51   #52  V          D2.0         N0.32 P0.10
54  L36   #52      R3 W25 D1.0         N0.11 P0.10
55  L34   #36      R7 W45 D1.4         N0.13 P0.12
56  L14   #35      R3 W85 D1.2         N0.12 P0.02
57  L104  #34      R3 W85 D4.0         N0.94 P0.31
58  L35   #57  V          D1.9         N0.46 P0.12
59  L54   #58  V          D1.3         N0.33 P0.14
60  L11   #58      R2 W70 D1.2         N0.16 P0.02
61  L48   #33      R3 W85 D0.9         N0.12 P0.10
62  L110  #33      R4 W70 D1.2         N0.14 P0.12
63  L71   #32      R2 W85 D1.5      C6
```

Fig. 1: Excerpt from a tree data file in *dtd* format. Each line describes a growth unit.

Fig. 2: Above-ground part of an 8 years old oak tree from the Lüneburger Heide (Germany), reconstructed with GROGRA (Kurth 1994). Visualization with AMAP-GLANCE (de Reffye & Blaise 1993).

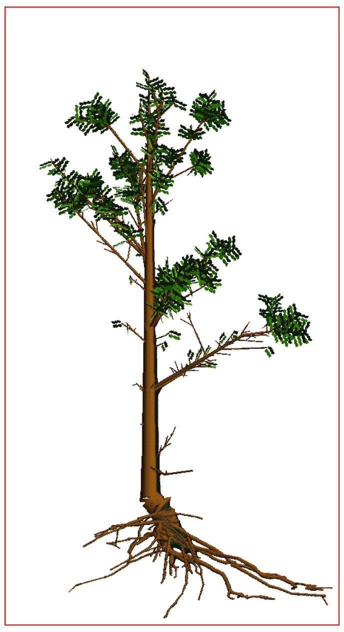


Fig. 3: A thoroughly measured, 11 years old oak tree, reconstructed with GROGRA, visualized with AMAP-GLANCE. Coarse roots were included down to a diameter of 5 mm.

Software interfaces

To facilitate exchange of data, comparison and validation of models and the conjoint use of structural information by several specialized models, interfaces for data transfer are essential (Fig. 4). Currently, GROGRA is interfaced with Adobe-PostScript, PovRay, DXF, HPGL, AMAP, AMAP-MTG (Godin & Caraglio 1998), HYDRA (Früh & Kurth 1999) and LIGNUM (Perttunen et al. 1996).

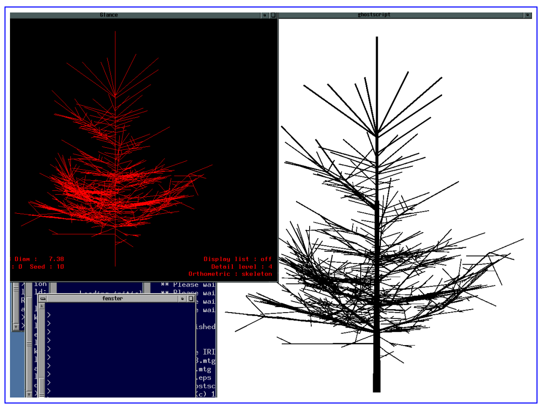


Fig. 4: Screenshot demonstrating the transfer of architectural data from GROGRA (PostScript output shown, right window) to AMAP-MTG (left window), opening the possibility to analyze structures with the powerful AMAPmod software (Godin et al. 1999).

Extraction of information about shoot population dynamics and branching

GROGRA (in connection with standard statistical software packages) provides facilities to "look into" the data from specific viewpoints, e.g. to deduce the age structure of the population of growth units (Fig. 5), to quantify morphogenetic gradients like acrotony (Fig. 6), or to check Leonardo's rule predicting equal sum of cross-section areas before and behind branching nodes (Fig. 7).

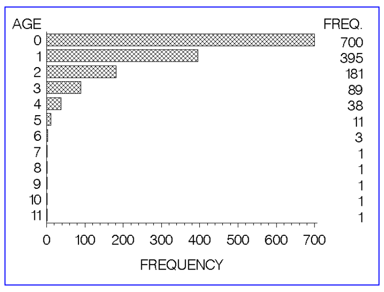


Fig. 5: Age distribution of the growth units of a 12 years old spruce tree (*cf.* Kurth & Anzola Jürgenson 1997; tree visualized in Figure 8).

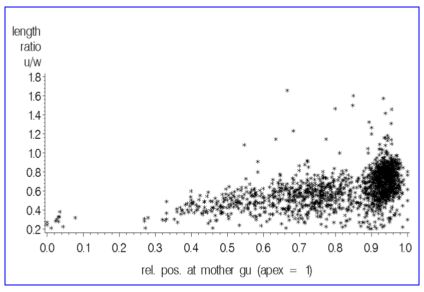
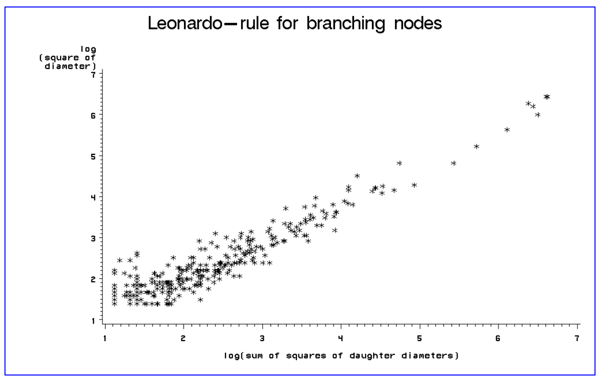
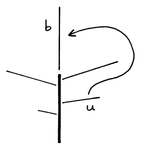


Fig. 6: Acrotonic tendency of shoot length in *Picea abies*. Ratio of shoot length *u* and length *v* of the corresponding "big brother" *b*, plotted against shoot position (data from a spruce branch, Kurth 1999).





"Big brother" *b* of a shoot *u*

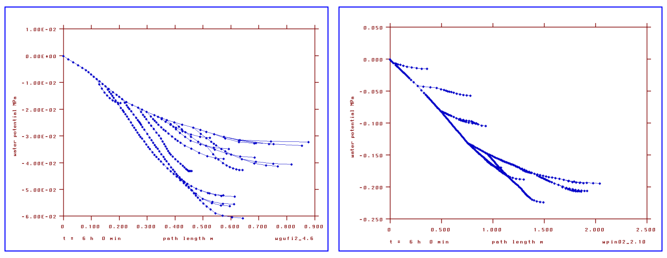
Fig. 7: Confirmation of Leonardo's rule in a spruce branch, i.e. preservation of cross-section area in branching nodes (*cf.* Oppelt et al. 2000b).

Towards assessing functional significance of tree architecture

The reconstructed tree structures (examples: Fig. 8) can be used by other, specialized software tools. The numerical, process-based model HYDRA (Früh & Kurth 1999) simulates the flow of water in the branching system of the tree crown and provides profiles of water potential along chosen paths in the crown (Fig. 9) as well as time series of water potential or flow (not shown). Thus, differences in hydraulic architecture between sample trees or between different species become apparent. HYDRA can also calculate local conductivity losses caused by cavitation events under drought, using empirical vulnerability curves (see Früh & Kurth 1999).

Fig. 8. Left: 12 years old spruce tree (see Kurth & Anzola Jürgenson 1997), height = 88 cm. Right: 10 years old Scots pine tree, height = 203 cm. Reconstruction of the trees with GROGRA, visualization with AMAP-GLANCE.

Fig. 9: Profiles of steady-state water potential along selected paths in the crowns of the trees shown in Fig. 8 (left: spruce, right: pine), calculated by HYDRA (Früh & Kurth 1999). Path length is measured from the base of the trunk.



Rule-based dynamic simulation of architectural development

L-systems (Prusinkiewicz & Lindenmayer 1990) and their extensions, growth grammars (Kurth 1994, 1999, 2000; Kurth & Sloboda 1999a,b) can serve as a formal basis to describe the growth of branching systems over many years. The software GROGRA reads such rule systems (Fig. 10; GROGRA = Growth Grammar interpreter) and calculates time series of 3-D structures from them. This simulation technique can be used to extrapolate morphological information from samples to large trees (Fig. 11) and to check hypotheses about shoot dynamics. Sensitive rules take environmental influences on growth into account (Kurth & Sloboda 1999b).

```
\const nbx 3,
\const nby 2,
\const dis 200,
\const ang0 50,
\const thr 40,  /* threshold value for distance function: 30 */
\var p0 uniform 0.85 1.,
\var p1 uniform 0.2 0.85,
\var ro uniform 0 360,
\var eps0 normal 0 5,
\var eps1 normal 0 10,
\var eps2 normal 0 30,
\var a table 0 15 25 32 37 40,
\var ai0 table 0 0 0 4,
\var ai1 table 0 0 0 2 4 8,
\var incr table 1.3 0.8,
\var k index,
\var b1 normal 100 30,
\var len length,
\var n distribution 0 0 0 0 0 0.1 0.4 0.3 0.2,
\var fdist function 2 1,
* # RL90 &(nbx) < [ &(nby) < [ RL-90 L(b1) P(10+k) D2 bud(0,0) ] f(dis) > ]
    RU90 f(dis) RU-90 >,
(o=0) bud(o,p) # gu(2.0,0) RH(ro)
    &(n) < [ @(p0) RH(k*360/n_+eps1) RL(ang0+eps0) an(1) L*0.65 bud(1,0) ] >
    RH(ro)
    &(3) < [ @(p1) RH(k*120   +eps2) RL(ang0+eps0) an(1) L*0.4  bud(1,1) ] >
    bud(o,p),
(fdist(10) > thr && (o=1 || o=2)) bud(o,p) # gu(incr(p),0)
    [ @(p0) RH15  RU(45+eps0) $ L*0.7 bud(o+1,p) ]
    [ @(p0) RH-15 RU(-45+eps0) $ L*0.7 bud(o+1,p) ] bn(1,p) bud(o,p),
(fdist(10) > thr && o=3) bud(o,p) # gu(incr(p),0) L*0.7 bud(4,p),
gu(delta,t) # gu(delta,t+1),
an(t) # an(t+1),
bn(t,p) # bn(t+1,p),
bud(o,p) ## P4 F3,
an(t) ## RL(a(t)),
(p=0) bn(t,p) ## RL(ai0(t)),
(p=1) bn(t,p) ## RL(ai1(t)),
gu(delta,t) ## D1+(delta*t) N1(80*len) U1(len) F
```

Fig. 10: Example of a sensitive growth grammar used by GROGRA to simulate architectural development of several competing spruce trees.

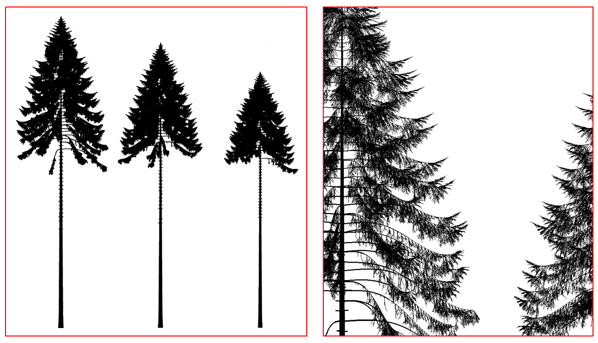


Fig. 11: 112 years old spruce trees of three different social classes (left), simulated with GROGRA, using a nonsensitive growth grammar based on branch samples from the Solling region (Germany). Right: Closer look at the virtual trees.

Comparison of rule sets and of models

The GROCOM software (Growth Grammar based Compound Model, Kurth 1999) combines the rule-based approach with process-oriented components. It includes several alternative light interception models, and furthermore a carbon allocation model from LIGNUM (Perttunen et al. 1996). Hence it is possible to compare the combined influence of assumed growth rules and radiation models (Fig. 12).

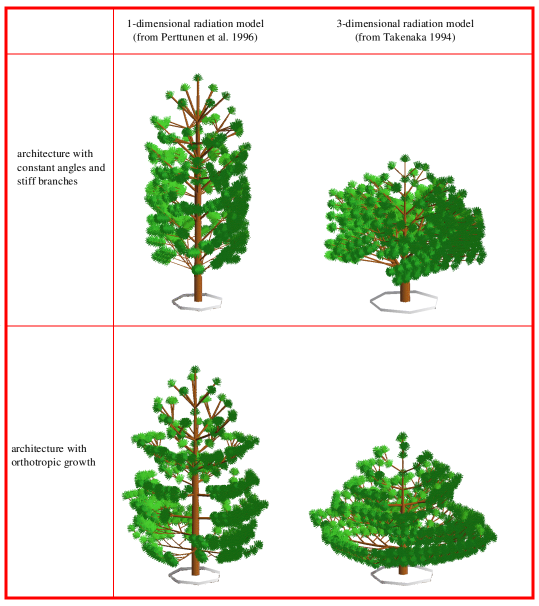


Fig. 12: Simulation of a solitary-grown 8 years old Scots pine tree by GROCOM. Different radiation and light interception models (columns) and different L-systems for branch geometry (rows) were used. The polygons below the trees symbolize the mass of the root compartment, which was not modelled as a 3-D branching system in this case. Graphical representation with AMAP-GLANCE (CIRAD, France).

Acknowledgements

We express our gratitude to François Houllier, Jean Dauzat, Christophe Godin, Jean-François Barczi and the other members of the AMAP team at CIRAD (Montpellier, France) for their support and for the possibility to use AMAP, and also to Risto Sievänen and Jari Perttunen from METLA (Vantaa, Finland) for good cooperation and access to LIGNUM. We thank Branislav Sloboda for his strong and continuous support. The funding of this work by the German Research Association (DFG) is gratefully acknowledged.

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