

# Appendices

*A method for estimating tree ring density by coupling  
CT scanning and ring width measurements: Application  
to the analysis of the ring width – ring density  
relationship in Picea abies trees*

---

*Silva INRAE*

Université de Lorraine, AgroParisTech, INRAE, Silva, 54000 Nancy, France

---

## Contents

---

A	Variation of the ring width–ring density relationship with height in the stem	3
B	Comparison of average air-dry densities between juvenile and mature wood	4
C	Ring width and density <i>versus</i> calendar year	5
D	Variations in the correlation between ring density and ring width as a function of calendar year	6
E	Number of annual rings <i>versus</i> height in the stem	7
F	Preliminary three-segment model	8
G	Model #1 taking as input cambial age ( $CA$ ) and height in the tree ( $H$ )	10
H	Model #2 taking as input cambial age ( $CA$ ), ring width ( $RW$ ) and height in the tree ( $H$ )	13

## APPENDIX A

---

### Variation of the ring width–ring density relationship with height in the stem

---

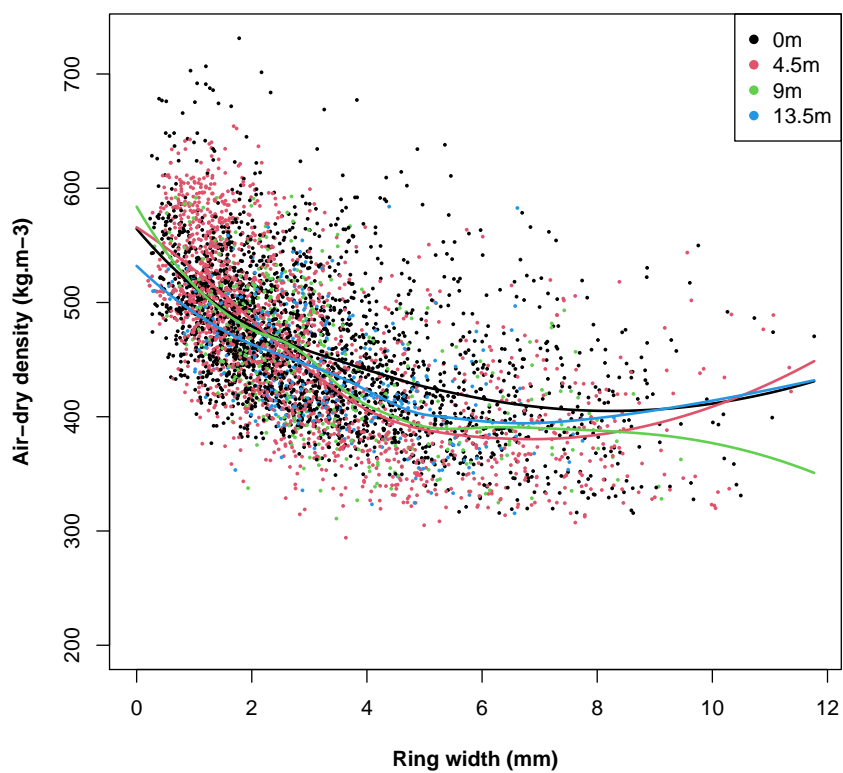


Figure A.1: Air-dry density as a function of ring width for the different estimated heights in the stem (0m, 4.5m, 9m and 13.5m). Trend curves for each height level are plotted.

## APPENDIX B

---

### Comparison of average air-dry densities between juvenile and mature wood

---

Table B.1: Average air-dry densities in juvenile and mature wood at each height level and significance of the differences obtained by performing t-tests. Rings less than 10 years old were assumed to belong to juvenile wood. The statistical significance is indicated by: ns:  $p \geq 0.05$ ; \*:  $0.05 > p \geq 0.01$ ; \*\*:  $0.01 > p \geq 0.001$ ; \*\*\*:  $p < 0.001$ .

Height in the stem (m)	0	4.5	9	13.5
Average density in juvenile wood ( $\text{kg.m}^{-3}$ )	497	388	394	402
Average density in mature wood ( $\text{kg.m}^{-3}$ )	457	485	469	458
T-test p-value	***	***	***	***

# APPENDIX C

## Ring width and density *versus* calendar year

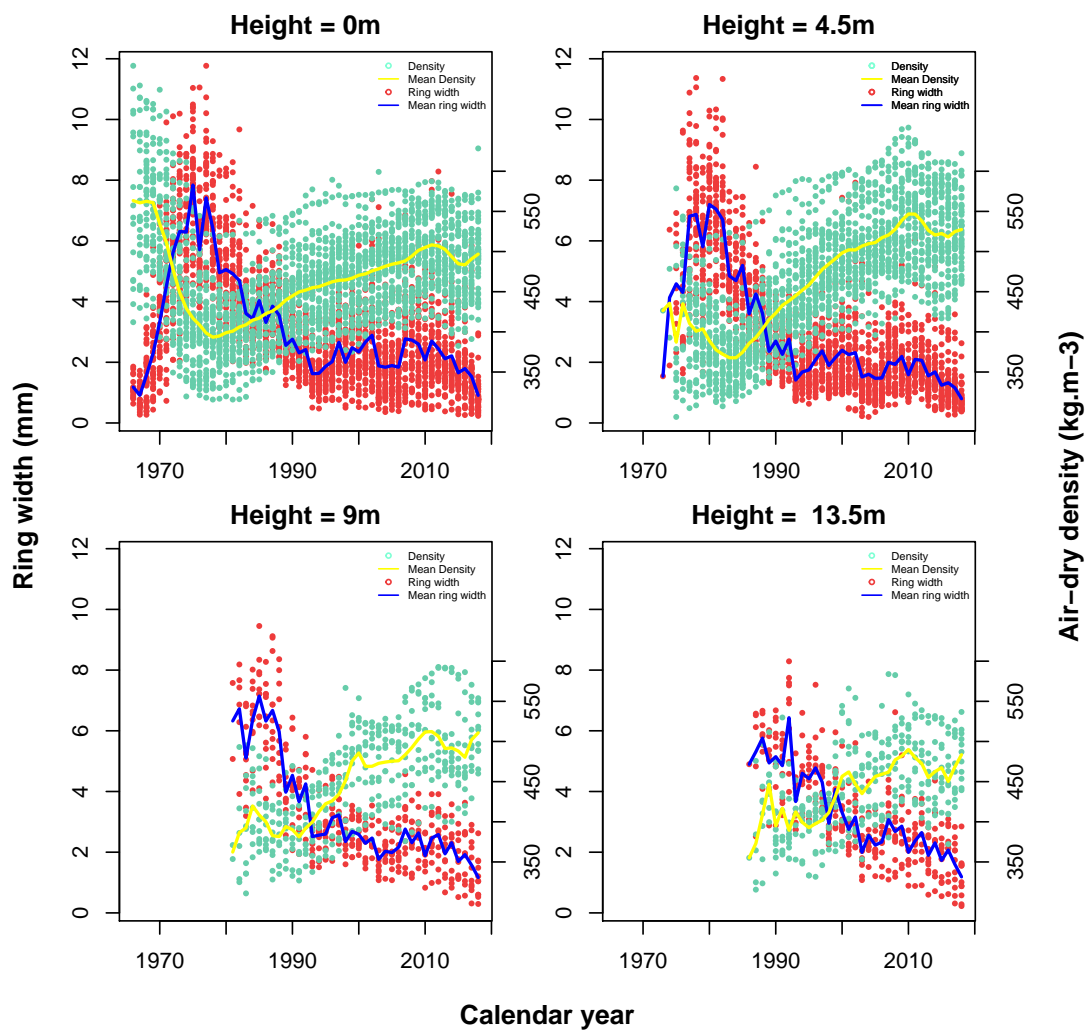


Figure C.1: Plot of ring width ( $RW$ ) and density ( $RD$ ) as a function of calendar year.

---

Variations in the correlation between ring density and ring width as a function of calendar year

---

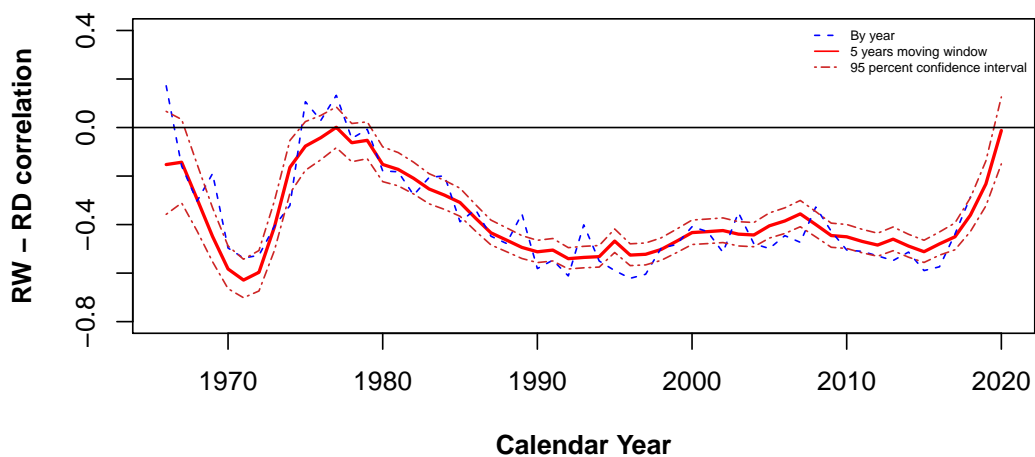


Figure D.1: Pearson correlation coefficient between air-dry ring density ( $RD$ ) and ring width ( $RW$ ) as a function of calendar year, including all height levels. The coefficients are computed for each year (dashed blue line) and then by using a five years moving window for the computation in order to obtain a smoothed curve (red line). A 95% confidence band is plotted for the smoothed curve (dashed red line).

## APPENDIX E

---

### Number of annual rings *versus* height in the stem

---

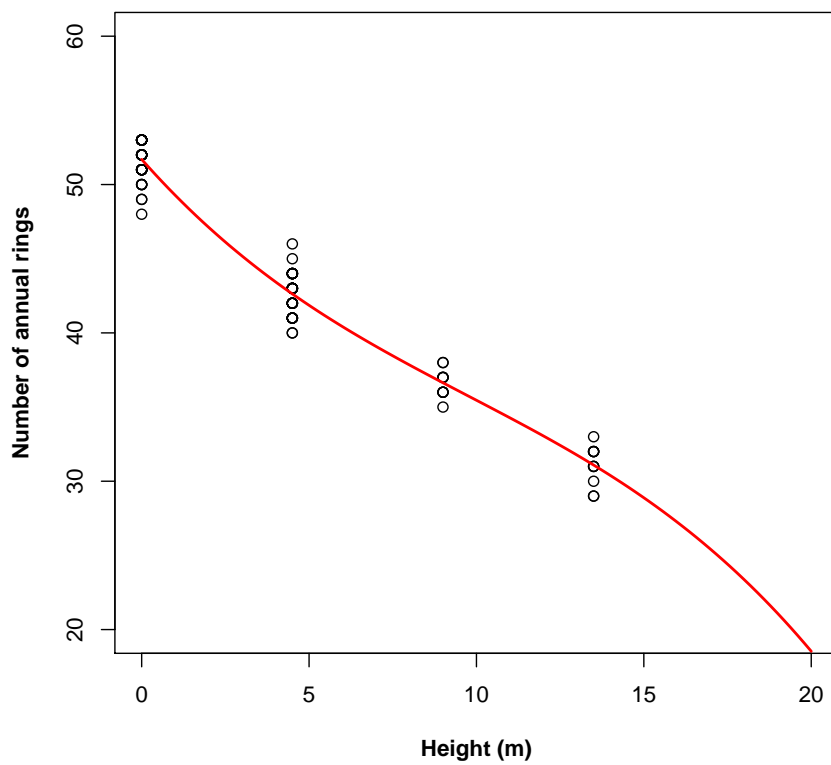


Figure E.1: Total number of annual rings measured at each height level in the stem (black circles) and extrapolation (red curve) up to 20 m using the `splinefun` function of R.

## APPENDIX F

---

### Preliminary three-segment model

---

Ring width and density both decrease over the last years of growth of the sampled trees (Fig. C). The decline seems to occur around year 2010, whatever the height level. For assessing more precisely the year of decline and verify if it depends on the height a three-segment linear model was fitted. The boundary between segments 1 and 2, supposed to correspond to the juvenile-mature transition, was assumed to depend only on cambial age, whereas the boundary between segments 2 and 3 was assumed to depend on growth year. Eq. F.1 was used to predict density in order to guarantee the continuity between the 3 segments:

$$\begin{aligned} d &= (a - c) \cdot x_0 + b \\ x_1 &= CA - GY + y_1 \\ f &= (c - e) \cdot x_1 + d \end{aligned} \quad WD = \begin{cases} a \cdot CA + b, & \text{if } CA \leq x_0, \\ c \cdot CA + d, & \text{if } x_0 < CA \leq x_1, \\ e \cdot CA + f, & \text{otherwise.} \end{cases} \quad (\text{F.1})$$

Where  $WD$  is the density,  $CA$  the cambial age and  $GY$  the growth year of the considered ring.  $a$ ,  $b$ ,  $c$ ,  $e$ ,  $x_0$  and  $y_1$  are the fixed parameters to be adjusted.  $x_0$  is the cambial age of the juvenile-mature transition and  $y_1$  the beginning year of the final decline.

The model was first fitted on the whole data-set, including rings from all 111 selected discs (see section 2.2), except ring #1 of each disc. Since the residuals of the general model were strongly dependant on disc height, mainly for the bottom disc, mixed models with random height effects were used to find exponential relations of most of the parameters with height. We finally arrived to the following relations:

$$\begin{aligned} x_0 &= x_{01} \cdot \exp(H)^{-1} + x_{02} \\ b &= b_1 \cdot \exp(H)^{-1} + b_2 \\ c &= c_1 \cdot \exp(H)^{-0.5} + c_2 \\ e &= 1 + e_1 \cdot c \end{aligned} \quad (\text{F.2})$$

Where  $H$  is the disc height.  $x_{01}$ ,  $x_{02}$ ,  $c_1$ ,  $c_2$ ,  $b_1$ ,  $b_2$  and  $e_1$  are fixed parameters to be fitted together with  $a$  and  $y_1$  of Eq. F.1.

To verify that  $y_1$  was not depending of height a mixed model based on Eq. F.1 and F.2 was adjusted with a random height effect on  $y_1$  (Table F.1). The `anova` test from the `stats` package of R showed that both models were equivalent



with  $y_1 = 2009.47$  whatever the height level. This suggests that the  $WD$  and  $RW$  decline begun just after 2009. Figure F.1 shows the  $WD$  values predicted by this model. Since the  $CA$  corresponding to 2009 depends on the disc, the intersect point between segments 2 and 3 also depends on the disc. The RMSE of the model is  $45.4 \text{ kg.m}^{-3}$  on the full dataset and  $45.1 \text{ kg.m}^{-3}$  when considering only the rings with  $GY \leq 2009$ .

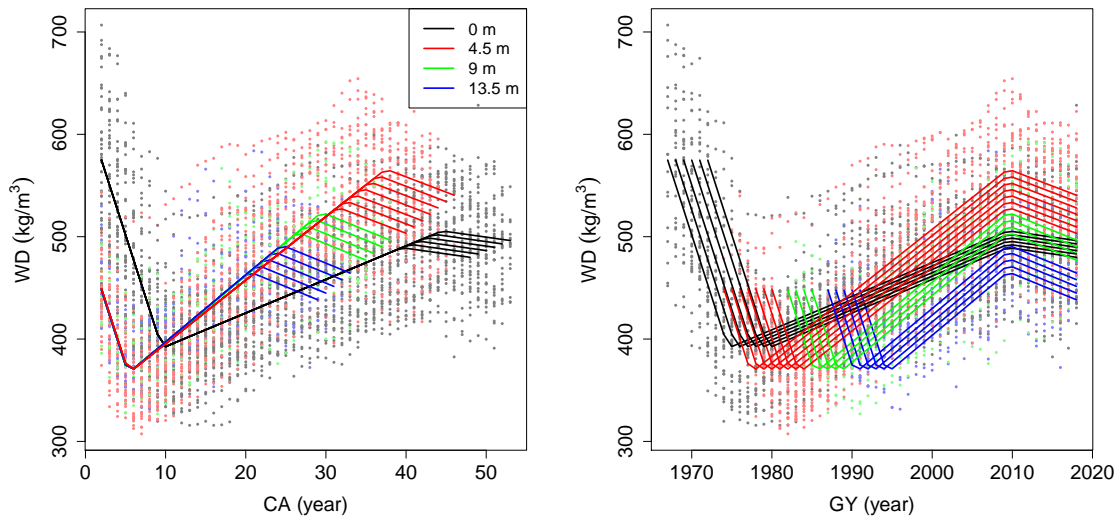


Figure F.1: Measured values of  $WD$  (points) and predicted values by the three-segment model of Eq. F.1 and F.2 (lines) in relation with  $CA$  (left) and  $GY$  (right) for each height level.

Table F.1: Fitted fixed parameters (estimates and standard errors in brackets) of the three-segment model of Eq. F.1 and F.2.

$a$	$y_1$	$x_{01}$	$x_{02}$	$c_1$	$c_2$	$b_1$	$b_2$	$e_1$
-2.43e+01	2.01e+03	5.33e+00	4.21e+00	6.55e+00	-3.27e+00	4.96e+02	1.27e+02	-6.42e-01
(9.57e-01)	(4.25e-01)	(1.29e-01)	(1.85e-01)	(1.44e-01)	(1.74e-01)	(4.38e+00)	(4.18e+00)	(1.06e-01)

## APPENDIX G

---

### Model #1 taking as input cambial age ( $CA$ ) and height in the tree ( $H$ )

---

Mixed models including a random effect corresponding to the height level on the parameters of the model of Eq. 1 were fitted one after the other to output the variations with height shown in Figure G.1.

The exponential relations of Eq. 2 were used in model #1 to account for these variations. The parameter  $a$  was let constant because the increase of  $a$  with the height in the tree led to too erroneous results in extrapolation (i.e., for heights above 13.5 m) with positive values of  $a$  whereas the slope of the first segment must remain negative.

The plot of residuals of model #1 versus ring width (Fig. G.2) shows a negative trend, especially for the smallest ring widths, which leads to model #2 including ring width.

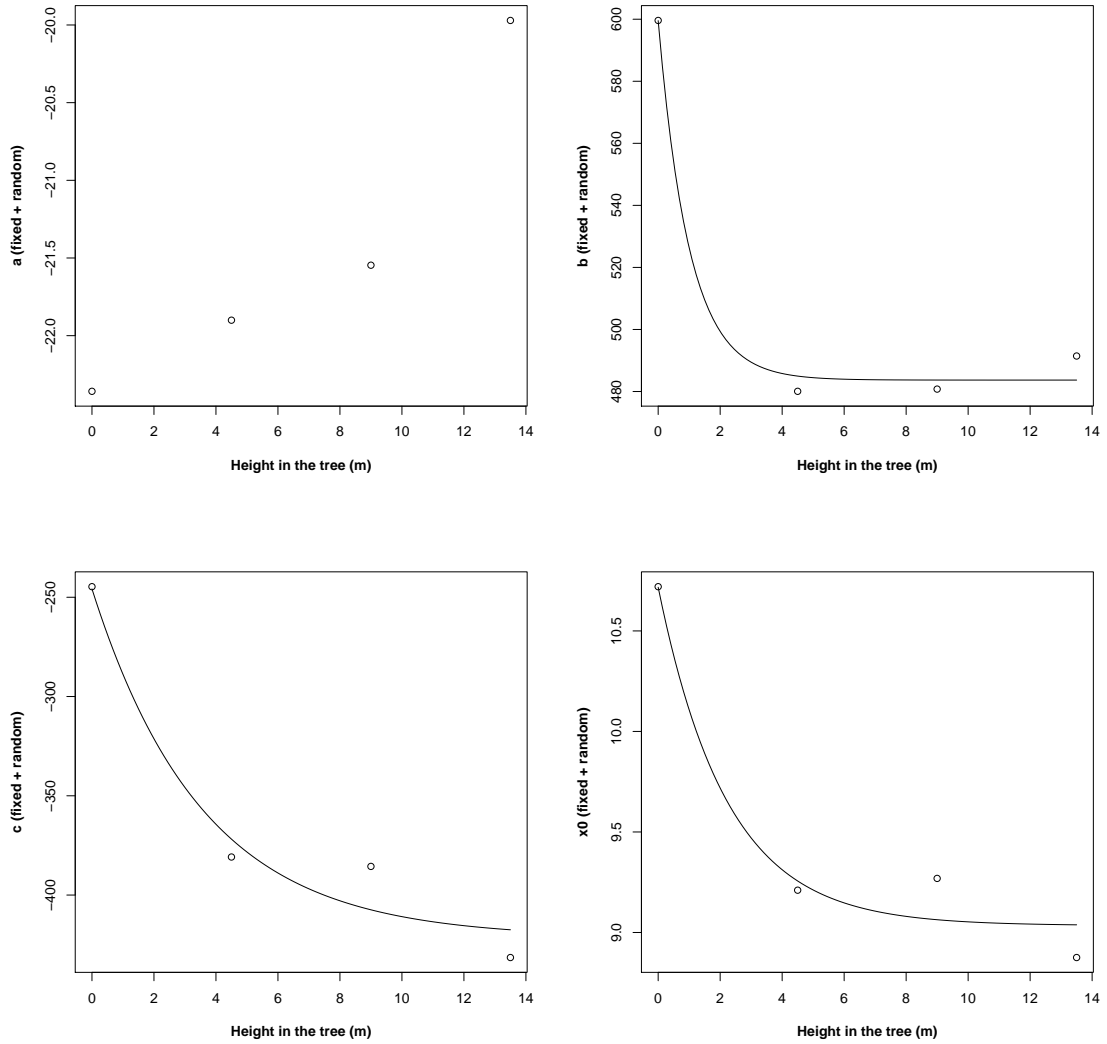


Figure G.1: Variation of parameters  $a$ ,  $b$ ,  $c$  and  $x_0$  according to the height in the tree ( $H$ ) for the piecewise model of Eq. 1 taking as input cambial age ( $CA$ ) only. The fitted models on plots for  $b$ ,  $c$  and  $x_0$  are of the same form as the set of equations given in Eq. 2.

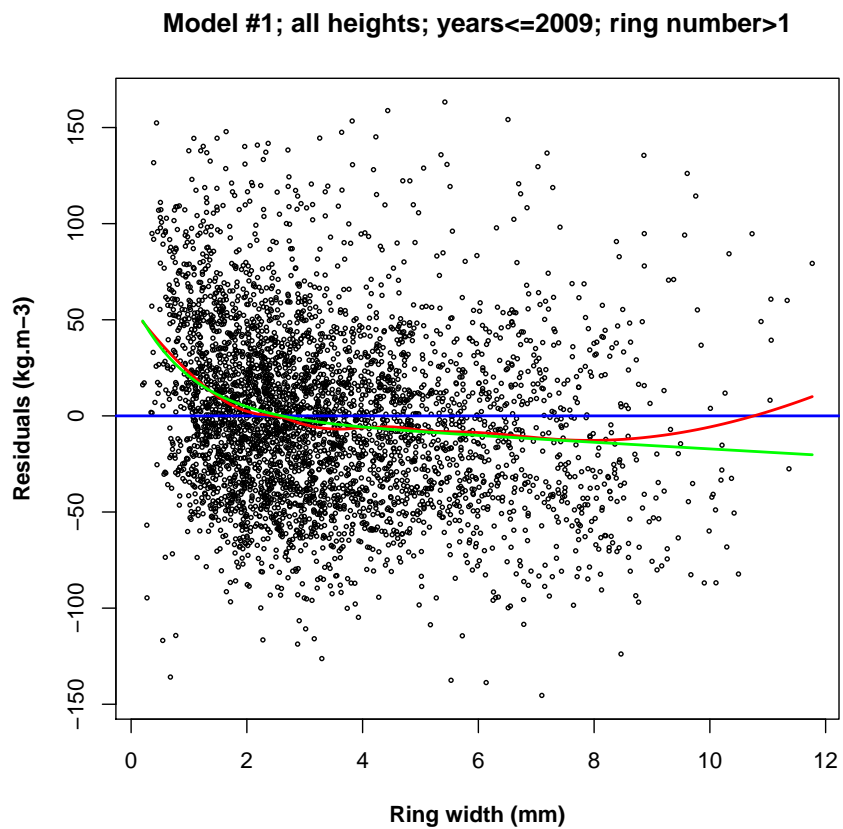


Figure G.2: Residuals of the final model #1 as a function of ring width ( $RW$ ). The trend curve is in red. In green, a model of the form  $residuals = f \cdot \exp(RW)^{-1} + g \cdot RW$ .

## APPENDIX H

---

Model #2 taking as input cambial age ( $CA$ ), ring width ( $RW$ ) and height in the tree ( $H$ )

---

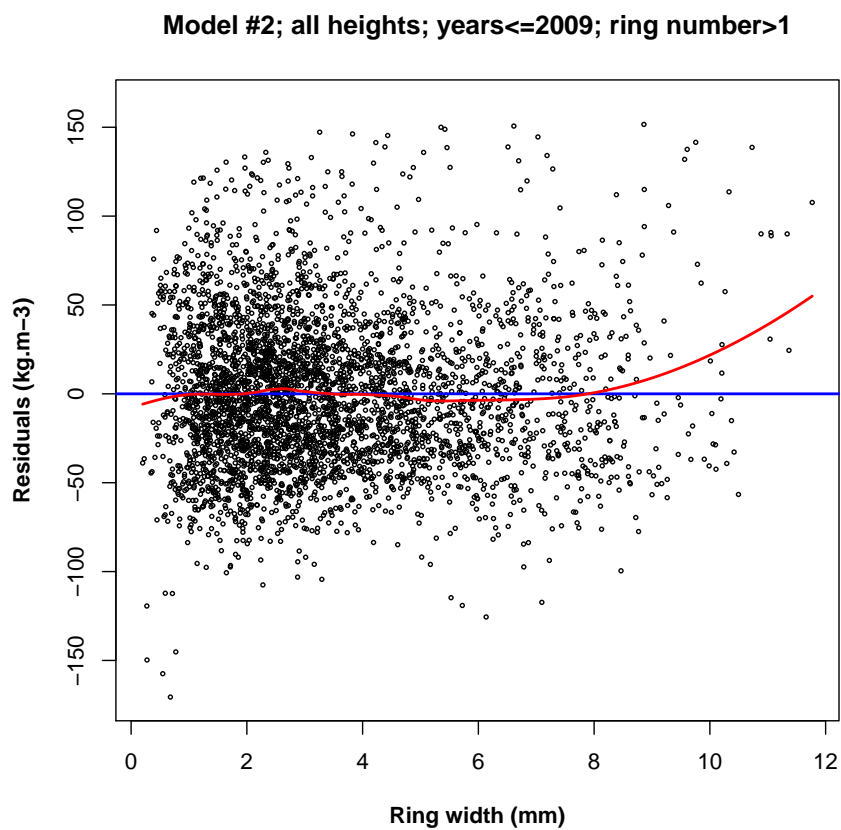


Figure H.1: Residuals of the final model #2 as a function of ring width ( $RW$ ). The trend curve is in red.