Available online at www.sciencedirect.com

SCIENCE DIRECT®

Ecological Modelling 169 (2003) 295–312

ECOLOGICAL MODELLING

www.elsevier.com/locate/ecolmodel

Predicting red heartwood formation in beech trees (*Fagus sylvatica* L.)

Thomas Knoke*

Department für Ökosystem und Landschaftsmanagement, Technische Universität München,
Am Hochanger 13, Freising 85354, Germany

Received 1 November 2002; received in revised form 14 May 2003; accepted 16 July 2003

Abstract

Beech forests (*Fagus sylvatica* L.) represent the natural vegetation cover for the majority of sites in Germany. Although coniferous forests actually dominate, beech is the most important among the deciduous-tree-species in Germany, when considering the area and the economics. While the wood of the younger beech normally shows a whitish colour (white beech), the timber of older beech may form coloured heartwood (facultative). This heartwood is highly variable in its colour. In most cases a reddish colour predominates, but sometimes the heartwood can be brown, grey, green, or even purple. Usually the coloured heartwood is called "red heartwood". As the uses of beech with "red heartwood" are restricted, mainly for aesthetical reasons, its presence severely reduces the timber quality. However, the existence of "red heartwood" cannot be distinguished until the tree is felled.

In this context the paper presents a possible new approach within the "red heartwood" research. The object is to predict the future "red heartwood" formation in beech trees, while they are actually still showing a bright colour. This information is relevant to improve the beech forest management. In order to provide this information the data of 392 felled beech trees were utilised. By means of a logistic regression analysis the probability of the occurrence of "red heartwood" was first analysed. Specific tree characteristics were tested as independent variables (age, diameter at 1.3 m height, crown base height, average diameter increment, injuries to the bark, forking). Transition probabilities (probabilities with which a recent "red heartwood" is formed) were then derived based on the statistical logistic regression function.

In order to predict the transition probabilities for still standing beech trees a model was formed comprising of tree characteristics as independent variables, which significantly influenced the "red heartwood" probability. Among the independents the age of the tree and the average diameter growth rate were the most important. The distance to the soil surface at which the heartwood was measured, and the number of injuries to the bark (dead branches, knobs, big scars), through which oxygen may enter the stem significantly influenced the transition probability. The presence or absence of a stem fork was also significant.

Keywords: *Fagus sylvatica*; Timber quality; Logistic regression; Transition probabilities; Future red heartwood formation

1. Introduction

Without the intervention of man Central Europe would be almost completely covered by forests (Ellenberg, 1986, p. 20). The Central European climate especially favours beech (*Fagus sylvatica* L.), which would dominate the natural vegetation cover.

---

* Present address: Fachgebiet für Waldinventur und Forstbetriebsplanung, Am Hochanger 13, Freising 85354, Germany.
Tel.: +49-8161-714700; fax: +49-8161-714616.
E-mail address: knoke@wbfe.forst.tu-muenchen.de (T. Knoke).

0304-3800/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0304-3800(03)00276-X

Because of the fact that beech is the native tree-species on most sites, the growing of beech is "… thought to better fulfil present and future demands for biodiversity by having more species associated than non-native tree-species". (Morsing, 2001, p. 7). Beech already mainly covers the deciduous forest area. Also from an economic point of view beech is the most important deciduous-tree-species in Central Europe. In Germany it covers an area of 1.43 million hectares (FMFAF, 1990, 1994), which is 15% of the total forest coverage.

The reason for the present day rather small proportion of beech lies in its relatively poor economic profitability of the past (e.g. Brandl, 1989). Economically, the production of a better timber quality could probably improve the financial returns in growing beech trees.

The colour of rather young beech-timber is normally whitish (white beech). In contrast to other tree-species the facultative formed coloured heartwood of beech, which is called "red heartwood", is regarded as a severe reduction in the timber quality (Necesany, 1969; Voß and Brandl, 1991; Höwecke and Mahler, 1991; Gfeller, 1998; Seeling, 1998; Spellmann, 1999; Tarp et al., 2000). In fact aesthetical reasons cause this devaluation of timber. The colour of the "red heartwood" varies from red to brown, green, purple, or grey, thus giving furniture or stairs an unsighty look (Rathke, 1996).

The "red heartwood" formation is an ecological phenomenon, which has been investigated by numerous studies (see Seeling et al., 1999 for an overview). From an economic point of view it is important that substantially higher prices can be derived for white beech logs rather than for those with "red heartwood". Several studies have been conducted to assess the economic loss by the "red heartwood" phenomenon (e.g. Seeling, 1998; von Büren, 2002). For example Richter (2001) reported yearly losses of 5.1 million Euro for North Rhine-Westphalia. Therefore, the avoidance of "red heartwood" formation would significantly improve the timber quality, its valuation and subsequently the economic returns.

If beech forms "red heartwood" (facultative), the heartwood develops rather late at an advanced age (e.g. Sachsse, 1991). In order to understand the phenomenon of "red heartwood" formation in standing beech trees, many studies investigated presumable relationships between stem characteristics and the heartwood attributes (for a detailed overview see Seeling et al., 1999). Most of the reports however, could not sufficiently quantify the influence of the relevant factors on the "red heartwood" characteristics. Among the literature analysed for this study, for example, no comprehensive set of statistical relationships could be found integrating that tree traits, which should according to the theory influence the "red heartwood". However, for the purpose of practical beech management as well as for having an ecologically based timber-quality-model for beech, the prediction of the "red heartwood" characteristics is of utmost importance.

This paper therefore aims at analysing and quantifying the influence of relevant factors, which have a significant impact on the presence or absence of "red heartwood" in standing beech trees ("red heartwood" probability). Special focus was then given the question of how to predict the future of "red heartwood" formation in beech trees, which actually still have a whitish timber colour (white beech). The results of this paper are part of a more comprehensive study on the "red heartwood" characteristics of beech trees, a research project which was funded by the "Deutsche Forschungsgemeinschaft".

In order to derive a model for the purpose of predicting "red heartwood" formation, this paper investigates the following two research questions:

1. *Which tree characteristics influence the "red heartwood" probability?*
2. *Which beech trees still showing a whitish timber colour will form new "red heartwood" in the future?*

2. Material and methods

2.1. Desired information and basic research approach

In Germany forestry has a long tradition. A basic felling rule has been established, which states that trees with the relatively worst timber quality are to be felled first while the better quality trees should be retained for further timber production (e.g. Krutzsch, 1952). Applied to the "red heartwood" problem this means that trees, which presumably contain "red heartwood" (called "red beech" from here on), should be harvested before beech with a white timber colour (subsequently called "white beech"). The simple and superficially logical cutting rule does not take into account that currently "white" beech may form "red heartwood" in the near future, and thus become devaluated by this process.

An earlier paper focused on the assessment of different felling strategies. The basic research question was whether the amount of "red beech" could be controlled if all the information about the heartwood of the standing trees were available (Knoke, 2002b). The results showed that only the information on potential future formation of "red heartwood" in currently still "white beech" can be utilised to improve the timber qualities produced, and subsequently improve the economic returns of beech management. Preferably felling the "red beech", as Krutzsch (1952) would generally have recommended, did not produce a better timber quality compared to felling a random selection of the trees.

It was concluded "... that if the beech management should be supported by heartwood information at all, only dynamic information on recent red heartwood formation in still white beech ... would seem to be efficient. Therefore, future research on the red heartwood of beech has to be designed in such a way that this information will be provided" (Knoke, 2002b).

Moreover, a methodological problem was identified in mobilising information on future formation of "red heartwood" for standing "white beech": "Once the stem has been felled it cannot be investigated regarding its heartwood formation at a later stage. The non-destructive measurement methods for beech heartwood are actually not yet far enough developed to be used in providing information on the red heartwood formation (von Büren, 2002; Weihs et al., 1999; Gruber, 2000). However, artificial time series analysis may be used to derive transition probabilities for white beech stems, which quantify the probability with which stems will form red heartwood in future. Möhring (1986) and Dieter (1997), for example, used a similar technique to integrate the wind-blow-risk in an economic evaluation. By relating the transition probabilities to stem properties like dbh, age, fork (yes/no) and the number of dead branches, stems with high transition probabilities could be identified and cut" (Knoke, 2002b).

Based on these findings the present paper tries to establish artificial time series on the probability with which "red heartwood" exists in beech stems. Using this data, the probability with which a beech tree moves from a "white" to a "red" heartwood colour was derived (transition probability).

2.2. *Sample stands*

During the winters of 1999/2000 and 2000/2001 392 harvested beech trees from 13 stands were recorded before towed from the forest. That meant the measurements took place directly in the forest stands after felling. The sample stands were located in five different growing regions. Mainly sites with ample water supply were represented. The mean stand-ages varied from 58 up to 180 years (Table 1), while the single-stem-age was between 58 and 222 years. Butt-logs with lengths between 2.9 and 19.0 m were cut from the felled trees.

Two sample stands which were formerly "coppice with standards"-forests ("Mittelwald"), where the dominant trees grew more or less without any competition (divisions Hirschruh belonging to the State Forest Office Arnstein and Brandrain belonging to the Community Forest Himmelstadt), were integrated in the study in order to represent trees with extreme properties (large crowns and fast growing rates). The average diameter of the sample stems from the "coppice with standards"-forests (about 70 cm) was greater than that from the comparably "high forest" stands ("Hochwald") by 10 to 20 cm, although the mean age was lower (Table 1).

2.3. *Variables*

2.3.1. *Dependent variable*

During the fieldwork it was recorded whether or not "red heartwood" was visible either at the bottom or at the top cut of the trees butt-log (i.e. the bottom stem section usually represents by far the highest financial value of the total stem when compared with the other stem sections). When stems with very small "red heartwood" were counted they were also categorised as "red heartwood". Several types of "red heartwood" exist, which are described by Sachsse (1991) and Seeling (1998) (Fig. 1). In this study only the classical "red heartwood"- and the

Table 1
Basic data on the sample stands ("coppice with standards"-forests ("Mittelwald") are printed fat and cursive; growing areas in brackets)

	Forest office (growing area)	Division	Site unit	Number of sample-stems	Mean age	Mean d1.3 (cm)	Mean height (m)
1	Rothenbuch (Spessart-Odenwald)	Kurzgrund	Fresh sands	32	140	55.0	37.2
2		Planke	Fresh sandy loams	22	161	59.5	33.8
3	Arnstein (Fränkische Platte)	Ochsen-knuck	Fresh and medium fresh fine-loams	27	166	49.3	35.9
4		***Hirschruh***	***Medium fresh and fresh fine-loams***	***26***	***147***	***70.0***	***32.2***
5		***Brandrain***	***Fresh fine-loam above lime***	***50***	***148***	***71.7***	***32.0***
6	Ebrach (Fränkischer Keuper und Albvorland)	Köhler	Medium fresh sandy loams and fresh sandy loams as well as loamy sands	34	180	56.3	34.3
7		Pflanzung	Fresh and very fresh sandy loams, medium fresh silt-loams	45	169	58.4	37.3
8	Eltmann (Fränkischer Keuper und Albvorland)	Dammersgrund	Medium fresh sandy loams	40	108	56.1	34.1
9		Kapelle	Medium fresh and fresh sandy loams	44	173	42.9	35.4
10	Zwiesel (Bayerischer Wald)	Sallerhäng	Fresh sandy gravel-loams	9	81	35.3	27.9
11	Schwabmünchen (Tertiäres Hügelland)	Brunnen	Fresh, gravely loams	13	126	43.3	32.1
12	University-Forest of the LMU Munich (Tertiäres Hügelland)	Galleneckerseige	Fresh fine-loam	39	58	33.7	24.5
13		Seeberg	Medium fresh sandy loam	11	78	41.0	35.4

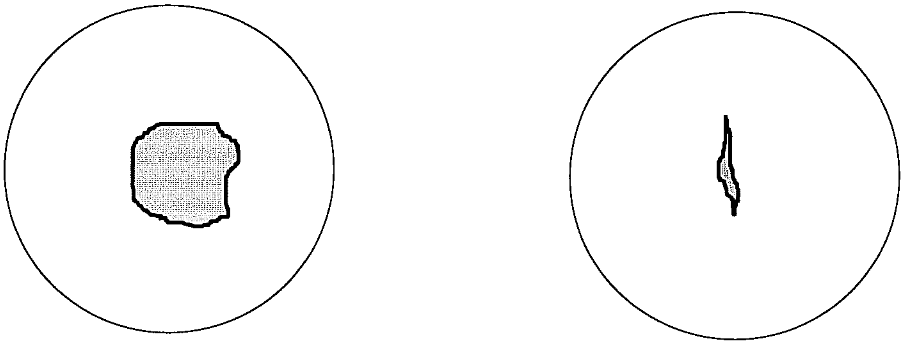
cracked "red heartwood"-types are analysed. For the other two heartwood-types (spattering and abnormal), which occurred rather seldom (in 8% of all cases) no biologically sound models could be derived.

Of course the analysis of merely the presence of "red heartwood"—with/without—simplifies the problem, as the diameter of the heartwood is also relevant for the loss in timber quality. Hence the present analysis is just a first step, which has to be supplemented by the analysis of the heartwood diameter during further studies. Already the presence of just a small "red heartwood" at the felling cut of beech stems may, however, cause substantially lower timber prices. In such cases the "red heartwood" at the top cut of the butt-log often amounts to more than 20% of the top diameter (Knoke, 2002a).

2.3.2. Independent variables

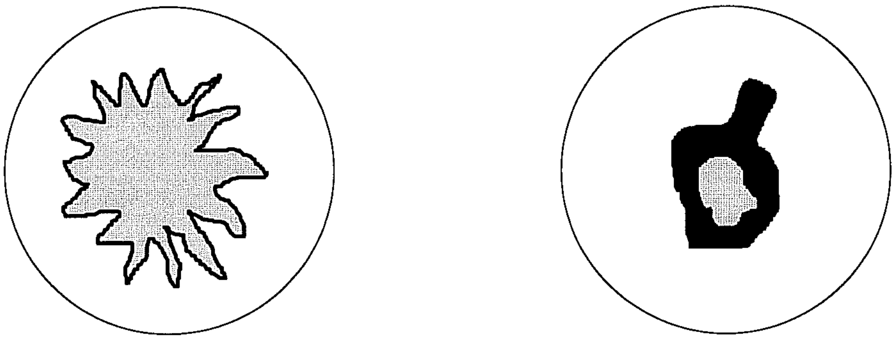
The independent variables to be tested should be consistent with the existing theory on "red heartwood" formation, which is briefly summarised in the following. According to Ziegler (1968) and Bosshard (1984) the heartwood formation in trees is generally a physiological process of cell ageing. Physiological waste products accumulate inside the parenchyma cells, the vitality of the parenchyma decreases and eventually may die back. However, this process alone merely leads to whitish heartwood but not to pigmentation of the cells. In fact, the "red heartwood" phenomenon does not occur before oxygen has entered central parts of older trees. The oxidation of the substances inside the less vital or dead parenchyma cells then takes place. It is assumed that dead branches or tree forks form entrances to the central stem parts (Zycha, 1948).

That means especially the *age* of the tree, the *number of injuries to the bark* through which oxygen may enter the stem and the presence or absence of tree *forks* influence the development of "red heartwood" according to the "red heartwood"-formation-theory (see Zycha, 1948; Ziegler, 1968; Sachsse, 1991). The



Classical red heartwood

Cracked red heartwood according to Klemmt (1996)



Spattering heartwood

Abnormal heartwood

Fig. 1. Schematic heartwood-types according to Sachsse (1991, with alterations, circles depict a schematic stem-disk).

increment rate may also have an influence on this phenomenon, as a faster growth rate may accelerate the ageing process (Bosshard, 1984). These variables formed the basis–variables of the model. Also the distance to the soil surface at which the "red heartwood" was observed was integrated into the model, as it is known that the "red heartwood" often forms the shape of a spindle in the vertical stem direction (Seeling, 1992).

2.3.2.1. Age. For the majority of the sample trees the age was determined in the laboratory, microscopically counting the annual rings of stem disks from a height of 0.15 to 12 m gained from trees in the sample stands. The exact procedure of calculating the tree age was described by Knoke and Schulz Wenderoth (2001). For some trees the exact stem ages could be obtained from Kennel (1972), who analysed experimental areas, which also served as a sampling area for the present investigation. Moreover, annual rings were counted directly at the tree-stumps of the sample-stems, where the sample stands were rather young (less than 80 years).

2.3.2.2. Diameter at 1.3 meters stem height (d1.3). The d1.3 between 24.0 and 100.6 cm were measured twice crosswise on the felled sample-stems using callipers.

2.3.2.3. Dead branches, knobs and scars (number of injuries in the bark). Visible dead branches, knobs and scars were counted as current or former injuries to the bark through which oxygen could have entered the stem. As a result of an earlier study (Knoke and Schulz Wenderoth, 2001) only the big dead branches with a diameter of more than 6 cm were counted. Furthermore, only scars of more than 9 cm were recorded.

2.3.2.4. Stem forks. The stem trait "fork" was integrated in the analysis by a dummy-code. A 1 was used for stems with a fork while stems without this property were coded with a 0.

2.3.2.5. Crown base and "red heartwood" distance to the soil surface. The crown base was defined as the height from the soil to the first living primary branch. The height at which the "red heartwood" occurred was also analysed and recorded, as the "red heartwood" often forms the shape of a spindle in the vertical stem direction. In order to obtain the distance from the "red heartwood" to the soil surface both the stump height and the butt-log-length were used.

2.3.2.6. Linear combination between basis–variables (interactions). Two interactions were tested in the present investigation. By means of the quotient d1.3/age (average diameter increment abbreviated as *id* from here on) it was verified whether the age had an influence on the parameter of the variable d1.3. This quotient represents not only an interaction but it may also be seen as a measurement for the average vitality of the tree.

During preliminary visual analyses of the data it became obvious that the stem trait fork did not have the same influence on the frequency of "red heartwood" for older stems compared to younger ones. The proportion of the "red heartwood" among young forked trees was very high compared to young non-forked trees. In contrast here to the proportion of "red heartwood" was almost the same regardless of the presence of a fork in the older stems. Apparently the importance of a fork is also age-dependent. Therefore, a second interaction variable between the stem trait fork and the age was introduced.

Naturally, an interaction variable is correlated with the basis–variables, which formed the interaction. In order to avoid or minimise autocorrelation, multiple regression analyses were carried out among the independent variables. Based on the r^2 the tolerance was calculated. Only combinations of variables, which had a tolerance above 0.2 were used. Actually the lowest tolerance was 0.53.

2.4. Data employed

Table 2 shows the number of stem cross sections of the different "red heartwood" types. The classical "red heartwood" was clearly dominant with 55% of all recorded stem cross sections belonging to this "red heartwood" type. Over all, "red heartwood" was more frequent at the top cut, while cracked, spattering and abnormal heartwood occurred more frequently at the bottom cut.

The variation of the dependent variables was great, as sample stems of former "Coppice with standards"-forests were included together with sample stems of the almost untreated experimental areas (Table 3). For example the d1.3 varied between 24.0 and 100.6 cm, the age between 58 and 222 years and the crown lengths comprised of intervals from 4.9 to 32.4 m.

The proportion of "red" stem cross sections increased from about 30% at an age of 80 years to 95% for trees older than 180 years. A similar effect could be observed when analysing the proportion of "red" stem cross sections depending on the d1.3 of the stems.

Overall, trees with a fork did not have "red heartwood" more frequently when compared with non-forked stems. Although among the relatively young stems (age less then 120 years) an effect of a

Table 2
Frequencies of different "red heartwood" types

"Red heartwood" type	Frequency (stem cross sections)	Proportion (%)	Bottom cut		Top cut	
			Frequency	Proportion (%)	Frequency	Proportion (%)
Without "red heartwood"	215	27	131	33	84	21
Classical "red heartwood"	433	55	169	43	264	67
Cracked "red heartwood"	76	10	49	12	27	7
Spattering heartwood	43	5	30	8	13	3
Abnormal heartwood	17	3	13	4	4	2
Sum	784	(100)	392	(100)	392	(100)

Table 3
Mean, standard deviation, minimum and maximum of the most important independent variables investigated

Sem trait	Mean	Standard deviation	Minimum	Maximum
d1.3 (cm)	53.8	14.9	24.0	100.6
Age (years)	138	39	58	222
Crown base height (m)	15.3	5.0	2.9	19.0
Crown length (m)	18.0	4.6	4.9	32.4
Tree height (m)	33.3	5.1	15.2	49.5
Injuries in the bark (number per tree)	4.1	3.8	0	29

stem fork was obvious. While non-forked trees only had in 30% of the cases "red heartwood", 50% of the forked trees showed "red" stem cross sections. Visually an influence of the number of injuries in the bark on the "red heartwood" frequency was hardly obvious.

2.5. Statistical method

Categorical variables like the colour of a stem section (either "white" or "red") can be introduced as dependents, for example in a logistic regression analysis (Hosmer and Lemeshow, 1989; SAS Institute, 1990), in a probit analysis (Weber, 1986; Schuemer et al., 1990) or in a discriminant analysis (Trampisch, 1985). By using any of these three methods, functions can be derived, which will allow estimating "red heartwood" probabilities.

It was decided to use the logistic regression analysis method to analyse the "red heartwood" probability. This method is simple and robust, and the SAS statistical program provides numerous diagnostical opportunities. A probit analysis was used in an earlier study (Knoke and Schulz Wenderoth, 2001). But the classification of stem cross sections either as "white" or as "red" based on the probit function was not successful enough. The same applies to the discriminant analysis, which was tested by Knoke (2002a).

The procedure LOGISTIC of the SAS program (Version 6.12) derives parameters (b_1–b_j) of a linear function. By means of this function abstract "logit-values" may be computed for a tree with a specific combination of stem traits (X_1–X_j):

$$\text{Logit}(w_i) = b_0 + b_1X_1 + b_2X_2 + \cdots + b_jX_j \qquad (1)$$

where Logit is the value to be put in the logistic function (Formula 2) in order to obtain a probability estimate within the interval between 0 and 1; w_i is the predicted "red heartwood" probability; b_0–b_j are the parameters of the function; X_1–X_j are the independent variables.

Based on Formula 2, which represents the logistic distribution function, it is possible to assign values between 0 and 1 to every "logit-value". These values can be seen as the probability with which one single stem will contain "red heartwood" ("red heartwood" probability). The logistic function is described by the following formula:

$$w_i = \frac{1}{1 + \mathrm{e}^{-\text{Logit}(w_i)}} \qquad (2)$$

where w_i is the predicted "red heartwood" probability for the ith stem cross section; Logit(w_i) is the logit-value according to Formula 1; e is the Euler's figure.

The parameter estimates for Formula 1 were obtained on the basis of single observations (SAS Institute, 1990). In order to assess the validity of the model, Pearson's residuals were computed according to the following Formula (e.g. SAS Institute, 1990, p. 1093, Hosmer and Lemeshow, 1989, p. 138):

$$r_i = \frac{y_i - n_i w_i}{\sqrt{n_i w_i (1 - w_i)}} \qquad (3)$$

where r_i is the residual (error-value) for the ith stem cross section; y_i is the observed value for the dependent variable. A 1 indicated the presence of a "red heartwood", a 0 was used for white stem cross sections; n_i is the number of observations with an identical combination of measured values for the independent variables; w_i is the predicted "red heartwood" probability for the ith stem cross section. Because of the great number of independent variables, for the present study, n_i was in most cases equal to 1. The denominator of Formula 3 can be seen as an estimate of the standard deviation. Consequently, the Pearson-residuals were standardised. They should have an approximate mean of 0 and a standard deviation of about 1, if the logistic regression model is correct (Hosmer and Lemeshow, 1989, p. 150).

The reduction of the sum of the squared residuals ("difference chi square", $\Delta\chi^2$, while χ^2 is computed as follows: $\chi^2 = \sum_{i=1}^{n} r_i^2$) was used to identify observations, which did not fit well into the model. According to Hosmer and Lemeshow (1989, p. 163), the observation was eliminated when the "difference chi square" was above a value of four.

The independence of the residuals is a central restriction for the logistic regression. This prerequisite was tested for the model function, which was based on two observations on a single tree (the "red heartwood" was recorded at the bottom and at the top cut of the tree's butt-log). The test was carried out using the Durbin-Watson value (Formula 4, SAS Institute, 1990, p. 1434).

$$d = \frac{\sum_{i=2}^{n}(r_i - r_{i-1})^2}{\sum_{i=1}^{n} r_i^2} \tag{4}$$

where d is the Durbin-Watson value; r_i is the residual (error-value) for the ith stem cross section; r_{i-1} is the residual (error-value) for that stem cross section before the ith stem cross section; n is the number of observations; d should be close to 2. Values between 1.5 and 2.5 were accepted to conclude that the independency of the residuals was given.

In order to assess the improvement of the model when an additional variable was introduced (the option "stepwise" was used to select the variables) the reduction of the -2-log-likelihood-value was analysed (-2LL). The -2LL becomes smaller when the estimated probabilities are either closer to 1 if "red heartwood" was present, or to 0 when no "red heartwood" occurred. The absolute value of the -2LL is of minor explanatory importance because -2LL is a sum-value, and it strongly depends on the number of analysed observations. The extent of its reduction after including a further variable into the model, however, characterises the influence of this variable.

The success of the classification of stem cross sections into the groups "red" (with "red heartwood") or "white" (without "red heartwood") was seen as the most important criterion for the quality of the model. The estimated "red heartwood" probabilities can be compared with a specific threshold value, for example 0.5. If the "red heartwood" probability is greater than the threshold value, the stem cross section was classified "red". If the "red heartwood" probability is less, then the stem cross section was assigned to the "white" group.

The classification test was carried out on the basis of those observations, which were used to estimate the parameters of the model. Furthermore, the same test was conducted utilising the data of 50 stems (which represented 100 stem cross sections), which were randomly selected. They were excluded from the data set, before estimating the parameters. This test-data-set was seen as independent from the main data set.

3. Results

3.1. "Red heartwood" probability

Several models were tested with different combinations of independent variables (Knoke, 2002a). Here, one model is presented, which is thought to be biologically sound and flexible enough to describe the real influence of the independent variables on the "red heartwood" probability. The model contains two interaction variables. The quotient d1.3/age, which is the *id*, was formed to integrate a measurement for the mean vitality of the stem. A probable effect of the age regarding the parameter of the d1.3 variable may be taken into account by this interaction variable. The second interaction is represented by the quotient for k/age. This variable was used, as the stem property fork seemed to have a greater influence for relatively young stems compared to older stems.

After the random selection of 50 stems (100 stem cross sections), which served as the test-data-set, and after the elimination of stems, which had spattering or abnormal heartwood, 625 stem cross sections could be utilised for the analysis; 186 stem cross sections showed no "red heartwood"; 439 had either classical "red heartwood" or a cracked "red heartwood".

3.1.1. The logit-function and its parameters

The resulting logit-function had the following structure:

$$\begin{aligned}\text{Logit}(w) = {} & b_0 + b_1 \times \text{age} + b_2 \times id + b_3 \times h \\ & + b_4 \times \text{injuries} + b_5 \times \text{fork} \times \text{age}^{-1} \\ & + b_6 \times h^2\end{aligned} \tag{5}$$

Table 4
Parameters of the logit-function for predicting the "red heartwood" probability (n after elimination of outliers 591, confidence limits according to the "Profile Likelihood"-option)

Variable	Order of affiliation	-2LL after affiliation	Parameter	Standard-error of parameters	P-value	Lower confidence limit	Upper confidence limit
Intercept		696	b_0: −19.4103	2.0078	<0.0001	−23.6158	−15.7196
Age	1	424	b_1: 0.1044	0.0098	<0.0001	0.0866	0.1250
id	2	379	b_2: 10.5659	1.7303	<0.0001	7.3125	14.1189
h	3	339	b_3: 0.4878	0.1123	<0.0001	0.2637	0.7089
fork × age^{-1}	4	321	b_4: 192.7	40.2196	<0.0001	115.6	274.0
Injuries	5	305	b_5: 0.1955	0.0540	0.0003	0.0946	0.3064
h^2	6	299	b_6: −0.0228	0.0089	0.0228	−0.0394	−0.0039

where age is the age of the stem in years; *id* is the average diameter increment in cm per year, which is formed by the quotient d1.3/age; h is the distance to the soil surface in meters if the stem would be still standing; injuries is the sum of actual and former injuries to the bark (dead branches above 6 cm, knobs and scars above 9 cm); fork × $\text{age}^{-1}$is the interaction between the stem trait fork (no fork = 0, fork present = 1) and the age. 5% of all observations were identified as outliers and therefore eliminated. The parameters of the model changed only slightly when more observations were used for the parameter estimation. The basic statistical characteristics, especially P-values and confidence limits for the parameters of the model are given in Table 4. The P-values show that the error-probability for assuming that the parameter differs from zero is less than 0.05 for all parameters. This indicates that the parameters of the variables included in the model are significant. Except for the parameters of "fork × age^{-1}" and "h^2" the P-values are less than 0.0001.

From a statistical point of view, the age has the greatest influence on the "red heartwood" probability. After introducing the age in the model, the -2LL was reduced by 272 points. This means that the "red heartwood" probabilities can be predicted much better if the age of the stem is known. The parameter of the age is positive, so the "red heartwood" probability becomes greater, as the analysed stems get older.

The integration of the *id* in Function 5 as a measure for the growth rate also reduced the -2LL substantially by 45 points. As mentioned earlier the *id* was computed as the quotient d1.3/age. Consequently, the age has an influence on the parameter of the d1.3. The older the stem, the less the "red heartwood" probability depends on the d1.3. The low increase of the "red heartwood" probability in old forest stands, if large stems are compared with smaller ones, can be explained by the fact that also small stems show a high "red heartwood" probability when they are old. The "red heartwood" probability shows a high level for all d1.3-dimensions. Fig. 2 illustrates this phenomenon.

Consequently, in the 180-years-old stand the value of the d1.3 has almost no influence on the "red heartwood" probability. In contrast to this, in the substantially younger 120-years-old stand the "red heartwood" probability strongly depends on the value of the d1.3. While small stems of this age show practically no case of "red heartwood", the "red heartwood" probability increases to 0.5 for large stems. Both curves demonstrate well the interaction between d1.3 and age regarding the "red heartwood" probability.

When two stems with the same d1.3 of 60 cm are compared, which are however, of different ages (120 and 180 years, respectively) the strong influence of the age becomes obvious. The younger stem exhibits a "red heartwood" probability of merely 0.34. In the case of the older stem it is more or less certain that it has already formed "red heartwood".

Analogous to the influence of the d1.3 the influence of the fork depends also on the age of the stem. Basically the presence of a fork increases the "red heartwood" probability compared to a stem, which has no fork. The older a stem is, the greater is the "red heartwood" probability. This also applies for a stem without a fork. Therefore, the influence of a fork decreases as the age increases. This effect is expressed by the age, which is used as the denominator of the interaction variable fork/age.

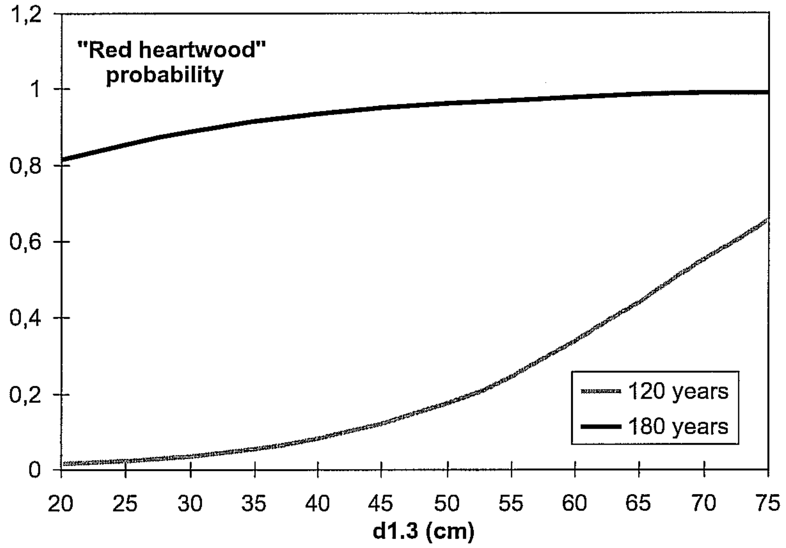


Fig. 2. "Red heartwood" probabilities in a 120-years-old stand compared to those of a 180-years-old stand (distance to the soil surface 0.3 m, 4 injuries to the bark and no fork).

3.1.2. Residuals and classification results

When using a randomly sorted data set, the Durbin-Watson value was 2.07. A sorting of the data set according to the stem number so that the two observations of one tree occurred directly after one another, resulted in a Durbin-Watson value of 1.75. Because both values are well between the critical limits of 1.5 and 2.5, it was concluded that the assumption of independent residuals is not violated. The standard deviation of the Pearson-residuals was 0.73 with a mean of 0.036. Fig. 3 depicts the variation of the residuals for the different growing areas investigated.

Within the growing area "Spessart-Odenwald" great "red heartwood" probability was sometimes predicted although no "red heartwood" was present. This is indicated by the large and negative residuals. In the "Bayerischer Wald" the residuals were large and positive in the most cases. This may indicate a site effect. Site effects were also tested (Knoke, 2002a), but are not reported here, as they did not significantly improve the model. The result that the site characteristics could not improve the model significantly might be explained by the fact, that the diameter growth rate *id* already implicitly reflects site effects.

In order to classify the stem cross sections by means of the obtained logit-function a classification threshold value had to be chosen. When a threshold value of 0.6 was used 88% of the observations, which served to estimate the parameters of Function 5, could be assigned to the right group. The relative error rate was only 9% for the "red" stem cross sections (Table 5). In contrast to this the 22%-error-rate for the "white" stem cross sections was higher.

The relative error rate for different predicted "red heartwood" probabilities is demonstrated in Fig. 4. It is obvious that the rate of error for predicted "red heartwood" probabilities was lowest either close to 0 or 1. For probabilities within the interval between 0.3 and 0.7 the rate of error was much greater. Only 22% of the overall predicted 591 probabilities, however, lay in this interval.

Table 5
Results of the classification of stem cross sections, which were used to estimate the parameters of Function 5

Stem cross sections	Classified as			
	Without "red heartwood"	With "red heartwood"	Sum	Error rate (%)
Without "red heartwood"	127	36	163	22
With "red heartwood"	38	390	428	9

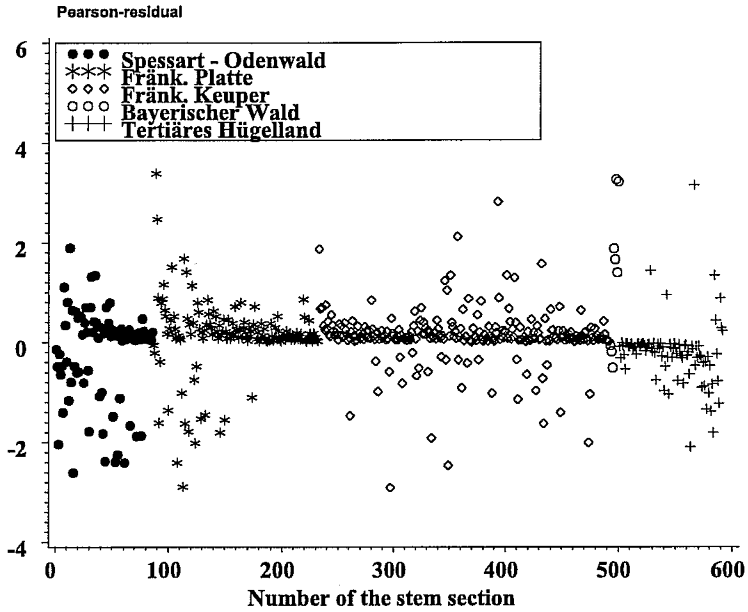


Fig. 3. Scatter plot of the Pearson-residuals for the investigated stem cross sections in the different growing areas.

The classification of the independent test-data-set proved to be correct in 76% of the 100 classified stem cross sections (Table 6).

The proportion of wrong classification results was also greater for the test-data-set among the "white" stem cross sections (28%) than among the "red" (23%). Particularly the relatively low error rate for the "red" stem cross sections is important because based on the logit-function the probability of the formation of "red heartwood" will be predicted.

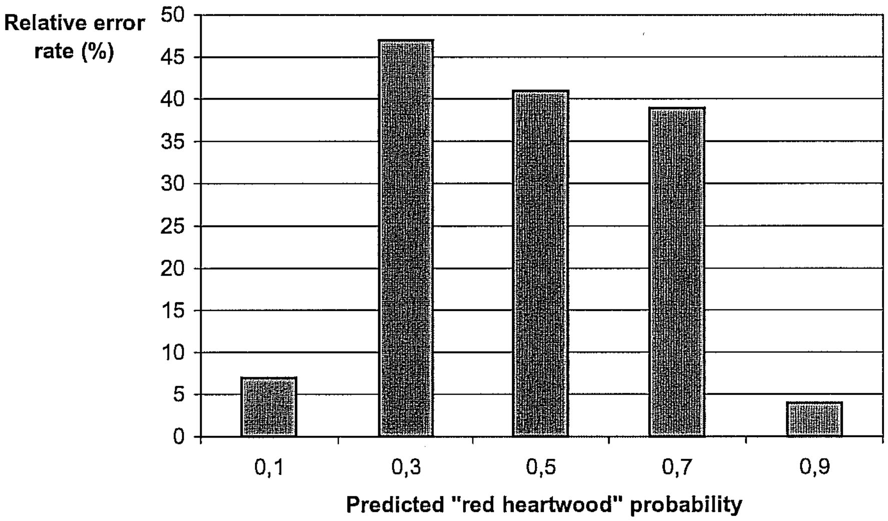


Fig. 4. Relative error rates for different predicted "red heartwood" probabilities.

Table 6
Results of the classification of stem cross sections of the test-data

Stem cross sections	Classified as			
	Without "red heartwood"	With "red heartwood"	Sum	Error rate (%)
Without "red heartwood"	21	8	29	28
With "red heartwood"	16	55	71	23

3.2. *Transition probabilities*

By means of the logit-function it is possible to predict the presence or absence of "red heartwood" with a specific error rate. But this prediction characterises merely a static condition of the tree. The prediction of a future "red heartwood" formation in a currently still "white" beech stem would be more essential, in order to improve the profitability of beech management.

As mentioned at the beginning the probability of a future "red heartwood" formation (which is from now on called transition probability) can hardly be measured directly. The problem is that the tree has to be destroyed to record the "red heartwood" properties. Although considerable work has been done to develop methods for measuring "red heartwood" on standing trees (von Büren, 2002; Weihs et al., 1999; Gruber, 2000) these methods are still not precise enough. Furthermore, even if these methods were to work precisely, long time periods would be necessary to observe "white" beech trees until they form "red heartwood".

As an alternative solution the results of the logistic regression can be utilised to derive transition probabilities. Of course these are not true probabilities as only static data is available. Based on an example, the derivation of the transition probabilities is explained as follows.

Let the proportion of actually 60-year-old trees with "red heartwood" be equal to zero. If this proportion is 10% for currently 70-year-old trees, the transition probability is assumed to be 0.1 for the period of 10 years. In this case at an age of 70 years 90% of the trees would still be "white". Furthermore, let the proportion of "red" trees at an age of 80 years be 30%. Then the difference in the relative proportion of "red" beech between ages 80 and 70 years is 20 percentage points. The transition probability is now derived through the number of trees among the 90% "white" beech in the 70-year-old stand, which must form "red heartwood" to get a proportion of 30% "red" trees in the 80-year-old stand. We get the transition probability by computing the quotient of the percentage-point-difference, that is the proportion of 80-year-old "red" trees minus the proportion of 70-year-old red trees, divided by the proportion of 70-year-old still "white" trees. Consequently, in this example the transition probability is 0.2/0.9, which results 0.22. This probability has a structural analogy to the so-called "hazard rate" used for example by Heckman (1976, 1979) to solve the problem of limited-dependent variables.

Based on the "red heartwood" probabilities predicted by means of the logit-function, transition probabilities were computed according to the method explained above. Fig. 5 illustrates the results for different situations. For the examples depicted here it was assumed that the stem's diameter would grow at a rate of 0.5 cm per year during the period being considered.

For the relatively young 60- and 80-years-old stems the transition probabilities are small, if the stems do not have many injuries to the bark and/or forks. A 60 cm large 100-years-old still "white" tree shows a transition probability of nearly 0.2. But if the same stem was forked the transition probability was almost twice as high as for the stem without a fork. The transition probability for a 60 cm large but already 120-years-old stem amounts to 0.36. Fig. 5

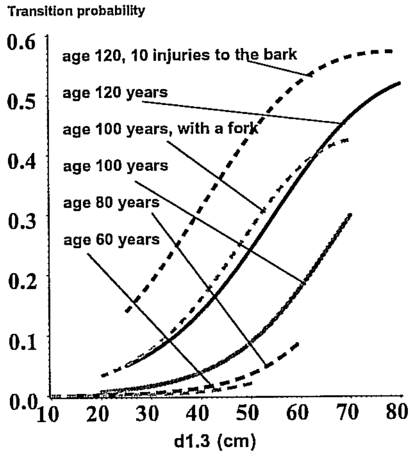


Fig. 5. Transition probabilities (probabilities with which new "red heartwood" will be formed with increasing age) for a period of 10 years (average diameter increment *id* 0.5 cm per year).

predominantly underlines the influence of the tree age on the transition probability.

3.3. Comparing the proportion of still "white beech" with the transition probability

The "red heartwood" properties, like the proportion of "white" beech trees and the transition probabilities may be computed for standard situations. An example is demonstrated in Table 7. When comparing the transition probability with the proportion of still "white beech" the data presented here can support the decision, whether to harvest a tree or to leave it growing in the stand.

According to Table 7 silvicultural interventions should be aimed at harvesting specifically those trees,

Table 7
Proportion of "white" beech trees and transition probabilities depending on several tree properties

		Proportion of „white“ beech stems (%)						Transition probability for ten years					
Age		d1.3-class (10 cm)						d1.3-class (10 cm)					
(y)	inj1)	20	30	40	50	60	70	20	30	40	50	60	70
80	0	100	100	100	99	95	-	0	0	0.01	0.02	0.08	-
	4	100	100	99	97	90	-	0	0	0.01	0.05	0.15	-
	9	100	100	98	93	77	-	0	0.01	0.04	0.12	0.28	-
	forked	99	98	92	75	45	-	0.01	0.03	0.09	0.22	0.37	-
90	0	100	100	99	98	94	84	0	0	0.01	0.03	0.09	0.22
	4	100	100	99	96	89	70	0	0.01	0.02	0.07	0.17	0.34
	9	100	99	97	90	74	47	0.01	0.02	0.06	0.16	0.32	0.48
	forked	99	96	88	74	48	22	0.02	0.04	0.12	0.26	0.40	0.49
100	0	100	100	99	97	92	81	0	0.01	0.02	0.05	0.13	0.26
	4	100	99	98	94	85	66	0.01	0.02	0.04	0.10	0.23	0.39
	9	99	98	94	86	67	42	0.02	0.04	0.10	0.22	0.38	0.52
	forked	98	95	87	70	45	22	0.03	0.07	0.17	0.31	0.44	0.52
110	0	100	99	98	95	89	74	0.01	0.02	0.04	0.09	0.18	0.32
	4	99	98	96	90	78	57	0.01	0.03	0.08	0.17	0.30	0.45
	9	98	96	90	78	56	37	0.03	0.08	0.17	0.31	0.46	0.56
	forked	96	91	81	61	37	19	0.06	0.13	0.24	0.38	0.49	0.55
120	0	99	98	96	91	81	64	0.01	0.03	0.07	0.15	0.26	0.40
	4	99	96	92	83	66	45	0.03	0.07	0.14	0.25	0.39	0.50
	9	96	91	81	64	42	23	0.07	0.15	0.28	0.41	0.52	0.58
	forked	83	67	46	27	13	6	0.11	0.21	0.34	0.45	0.53	0.56
130	0	98	96	92	84	69	50	0.03	0.07	0.14	0.24	0.36	0.47
	4	96	92	84	70	51	31	0.07	0.14	0.24	0.36	0.48	0.55
	9	90	82	66	47	28	15	0.16	0.27	0.40	0.51	0.57	0.60
	forked	69	50	31	17	8	4	0.20	0.31	0.43	0.51	0.56	0.58

1) inj=number of actual or former injuries to the bark;

shaded cells: trees with these properties should preferably be harvested which are most likely still white and while their transition probability is high (indicated by a grey colour in Table 7). Up to an age of 80 or 90 years stems without forks and injuries to the bark can be retained in the forest stands without much risk of a "red heartwood" formation. If those stems show more than four bark-injuries and/or a fork their transition probabilities are much higher, which indicates a considerable risk for future "red heartwood" formation (between 0.15 and 0.37). Such stems should preferably be harvested thus supporting the better ones.

In contrast to the situation in relatively young stands, even the stems of a good timber quality ("white" stems without forks and bark-injuries) should be harvested in the old stands. In these old stands the trees, which are forked and have bark-injuries have almost certainly already formed "red heartwood". Their timber quality is therefore poor with little risk of deterioration in the future. The harvest has to be concentrated on the good stems, which will most likely form "red heartwood" in the near future.

4. Discussion

Before the results achieved and the methodology applied can be discussed, the following research questions formulated at the beginning of this paper require a brief answer:

1. *"Which tree characteristics influence the "red heartwood" probability?"*
2. *"Which beech trees still showing a whitish timber colour will form new "red heartwood" in the future?"*

The tree traits age, average diameter increment (growth rate), number of injuries to the bark and stem fork significantly influence the "red heartwood" probability and the transition probability. Their influence could be combined within a biologically sound model. In contrast to the opinion of other authors, like Racz et al. (1961), Becker et al. (1989) Höwecke (1998), and Richter (2001), the age was the most important independent variable.

4.1. Methodological approach

The present study might have suffered from the fact that only harvested trees could be utilised. The forester often decides that stems with a low timber quality are to be cut, which are preferably stems with big knobs, dead branches or forks. This fact could have led to a poor representation of the real "red heartwood" situation by the sample stems. The mentioned stem characteristics have, however, been integrated in the analysis. Thus the restriction of the results by potentially poor representative data should be more or less small.

By means of the transition probabilities the "red heartwood" phenomenon was analysed dynamically. This made the results probably more suitable for use as support regarding the felling decision. The transition probabilities were, although based on the dynamic interpretation of several static conditions, seen as a time series. This method was critically reviewed by Pretzsch (1999). He pointed out that the history of the sample stems sometimes differs greatly. This means it may become problematic to consider sample stems analysed simultaneously as a time series. So far alternatives to the method presented within this paper, i.e. time-efficient methods, which do not destroy the stems, seem not to exist.

4.2. Progress for modelling timber quality on an ecological basis

In recent years it was intensively discussed among ecologists to use more theoretically based research approaches to explain ecological observations, correlations and rules (Jørgensen, 2002; Marques and Jørgensen, 2002; Odum, 2002). For this purpose, the theoretical basis provided by system ecology should be used.

The model presented in this paper describes just one ecological phenomenon, the "red heartwood" formation, which greatly depends on the forest ecosystem characteristics. The occurrence of this phenomenon is largely driven by interactions between the trees. The competition of neighbour trees determines how fast a beech tree may grow by controlling mainly the diameter growth rate (e.g. Bryndum, 1987). Moreover, great competition because of a high stand density causes tree branches to die, which then form injuries to the bark through which oxygen may enter the stems central parts, where "red heartwood" formation is then induced. By integrating such variables in the model equations the timber quality, which is greatly dependent on the "red heartwood" characteristics, can now be modelled on an ecologically sound basis.

Although rather seldom, other models on the "red heartwood" probability exist. Börner (1998) for example developed a hyperbolic function on the "red heartwood" probability depending merely on the d1.3 of the trees. That would mean that a tree of one specific d1.3 always shows the same "red heartwood" probability regardless of its age, the number of injuries to the bark, and the presence/absence of a fork. There does not seem to be a great theoretical support for such a model. Also Kügler's (unpublished) model, which was used by Zell et al. (2003) for an optimisation of beech management, was just based on the d1.3, the mean height of the stand and the distance to the soil surface. However, this model is superior compared to Börner's model, as the mean height development roughly reflects the mean age of the trees. In contrast to the model described within this study, the successful classification by Kügler's model was 74%, while the present model resulted in 88%. Von Büren (2002) presented logit-models for the "red heartwood" probability, which contained similar variables compared to the present model. However, she ignored the growth rate and the distance to the soil surface. Both variables significantly improved the present model. The growth rate as a dynamic variable seems to be particularly important. The amount of successful classifications achieved by von Büren's models were only between 75 and 68%. An independent data set was not used to test the models.

Moreover, none of the described existing models allow predicting the future "red heartwood" formation. A comparable approach to quantify transition probabilities in order to provide information on the probability with which new "red heartwood" will be formed in future does probably not exist at all. Particularly this information shows the most potential to improve the beech management (see Knoke, 2002b). Transition probability approaches were, however, often used for the purpose of modelling other dynamic ecological phenomena. Transition matrix based "Markov models" were used for example to construct forest growth models (Buongiorno and Michie, 1980) or to describe successional dynamics (Childress et al., 1998). Also the tree mortality was often modelled on the basis of survival probabilities, which were derived from logistic functions (e.g. Yang et al., 2003). Consequently, the application of the transition probability approach to the "red heartwood" formation phenomenon seems to be a step forward in modelling timber quality of beech.

The model presented in this paper agrees with the theory on "red heartwood" formation (Chapter 2.3.2) better than the existing models on "red heartwood" characteristics. The statistically significant influence of the stem characteristics "age", "diameter growth rate", "injuries to the bark" and "fork" on the "red heartwood" probability is consistent with the "red heartwood"-theory (see Zycha, 1948; Ziegler, 1968; Bosshard, 1984 and Sachsse, 1991). This influence could be well quantified by the model, which was not the case for most of the already existing studies analysed during the literature review. Furthermore, the present model allows an ecologically sound estimation of the "red heartwood" probability, because the probability estimate is based on tree traits, which are greatly sensitive to the environment in which the tree grows.

4.3. *Linking transition and "red heartwood" probabilities with a growth model*

As explained above both models derived in this paper ("heartwood" probability and transition probability) are mainly driven by tree traits, which greatly depend on the growing environment of the tree. Because of the sensitivity of the tree traits to the competition by neighbour trees, the models can be well linked with single tree growth simulators, which are mainly driven by the same force (as for example the growth model Silva of Kahn and Pretzsch, 1997). This would be advantageous in order to predict the development of the timber quality of beech and subsequently the economic returns. Two different approaches seem possible:

First, the "red heartwood" probability may be linked with the growth model. In this case the current "red heartwood" state ("red heartwood" present or absent) is estimated after the harvest of the stem was simulated. The standard deviation of the prediction can be computed as $\sqrt{n \times \mathrm{pr} \times (1 - \mathrm{pr})}$ (with n being the number of trees with an identical combination of the independent variables and pr being the "red heartwood" probability).

Second, the "red heartwood" formation can be predicted on the basis of the binomial distribution using the transition probability as its expected value. Similar to the first approach the standard deviation of this prediction can be computed as $\sqrt{n \times \mathrm{pt} \times (1 - \mathrm{pt})}$ (with n being the number of trees with an identical combination of the independent variables and pt being the transition probability). This prediction can, however, only be done if the diameter growth is known at the beginning of every simulation.

For both approaches information on the number of injuries to the bark and the presence/absence of a fork was required.

4.4. Further research

The effectiveness of the transition probabilities when used to decide whether a tree is to be felled or not should be tested. This is possible by a simulation approach similar to the method applied earlier (Knoke, 2002b). In contrast to the method applied for Knoke's investigation, the uncertainty rate must be integrated by means of the error rates, which occurred during the statistical analysis.

A silvicultural management strategy, which assigns predominantly the trees with high transition probabilities to be harvested, should produce more "white" beech timber than other management strategies, if the transition-probability-estimate is to be a useful harvest-indicator.

Moreover, the diameter of the "red heartwood" if present must be modelled in order to obtain a sound measure for the severity of the devaluation of the stem. This can be done by the linear regression method (Knoke, 2002a).

5. Conclusions for forest practice

According to the presented results it seems likely that a fast growing tree may achieve a specific diameter at a lower risk of being devaluated by "red heartwood". Moreover, the quantification of the effects of injuries to the bark showed that the importance of this tree trait is not as great as it was assumed by Wilhelm et al. (1999, 2001).

Up to an age of 80 or 90 years stems without forks and injuries to the bark do not bear much risk of a "red heartwood" formation. If those stems show more than four bark-injuries and/or a fork a considerable risk for future "red heartwood" formation (between 0.15 and 0.37) could be found.

Comparing the situation in relatively young stands to the old stands, those trees which are forked and have bark-injuries have most certainly already formed "red heartwood". While the good stems without a fork and/or bark-injuries may still be white but could most likely form a new "red heartwood" with increasing age.

Acknowledgements

The author wishes to thank Dr. Bernd Stimm, PD Dr. Christian Ammer, the Editor-in-Chief of Ecological Modelling and two anonymous reviewers for useful comments as well as Mrs. Edith Lubitz for the language editing of the manuscript.

References

Becker, D., Freist, H., Øllgaard, M., 1989. Zielstärkennutzung und Buchenrotkern. Forst. und Holz. 44, 12–14.

Börner, M., 1998. Zu Wachstum und Wachstumsreaktion der Rotbuche (*Fagus sylvativa* L.) nach Freistellung im fortgeschrittenen Alter. Lincom Studien zur Forstwissenschaft 03. Lincom Europa academic publishers

Bosshard, H.H., 1984. Holzkunde Band 2. 2., überarbeitete Auflage. Birkhäuser, Basel.

Brandl, H., 1989. Ergänzende Untersuchungen zur Ertragslage der Baumarten Fichte, Kiefer, Buche und Eiche in Baden-Württemberg. Allgem. Forst- u. J.-Ztg. 160, 91–98.

Bryndum, H., 1987. Buchendurchforstungsversuch in Dänemark. Allg. Forst- u. J.-Ztg. 158, 115–121.

Buongiorno, J., Michie, B.R., 1980. A matrix model of uneven-aged forest management. Forest Sci. 26, 609–625.

von Büren, S., 2002. Der Farbkern der Buche (*Fagus sylvatica* L.) in der Schweiz nördlich der Alpen. Beiheft zur Schweiz. Z. Forstwes. Nr. 86.

Childress, W.M., Crisafulli, C.M., Rykiel Jr., E.J., 1998. Comparison of Markovian matrix models of a primary successional plant community. Ecol. Model. 107, 93–102.

Dieter, M., 1997. Berücksichtigung von Risiko bei forstbetrieblichen Entscheidungen. Schriften zur Forstökonomie, Bd. 16, J.D. Sauerländer's, Frankfurt/Main.

Ellenberg, H., 1986. Vegetation Mitteleuropas mit den Alpen aus ökologischer Sicht. 4., verbesserte Auflage. Ulmer, Stuttgart.

FMFAF (Federal Ministry for Food, Agriculture and Forests) 1990. Bundeswaldinventur 1986–1990. Bundesministerium für ELF, Bonn.

FMFAF (Federal Ministry for Food, Agriculture and Forests) 1994. Der Wald in den neuen Bundesländern. Bundesministerium für ELF, Bonn.

Gfeller, B., 1998. Weisses und verkerntes Buchenholz in der Holzwirtschaft. Schweiz. Z. Forstwes. 149, 943–953.

Gruber, F., 2000. Messergebnisse zur Identifizierung von Buchenfarbkernen (*Fagus sylvatica* L.) mit den Bohrmessgeräten Teredo und Resistograph 1410 sowie dem Impulshammer-Schallmesssystem. Allg. Forst- u. J. Ztg. 171, 117–123.

Heckman, J.J., 1976. The common structure of statistical models of truncation, sample selection and limited dependent variables and a simple estimator for such models. Ann. Econ. Soc. Meas. 5/4, 475–492.

Heckman, J.J., 1979. Sample selection bias as a specification error. Econometrica 47, 153–161.

Hosmer, D.W., Lemeshow, S., 1989. Applied Logistic Regression. Wiley and Sons, New York.

Höwecke, B., 1998. Untersuchungen zum Farbkern der Buche (*Fagus sylvatica* L.) in Baden-Württemberg. Schweiz. Z. Forstwes. 149, 971–990.

Höwecke, B., Mahler, G., 1991. Untersuchungen zur Farbverkernung bei der Rotbuche (*Fagus sylvatica* L.) in Baden-Württemberg. Mitteilungen der Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg, Heft 158, Teil I.

Jørgensen, S.E., 2002. Explanation of ecological rules and observation by application of ecosystem theory and ecological models. Ecol. Model. 158, 241–248.

Kahn, M., Pretzsch, H., 1997. Das Wuchsmodell SILVA-Parametrisierung der Version 2.1 für Rein- und Mischbestände aus Fichte und Buche. Allg. Forst- u. J. Ztg. 168, 115–123.

Kennel, R., 1972. Die Buchendurchforstungsversuche in Bayern von 1870 bis 1970. Forstliche Forschungsberichte München No. 7.

Knoke, Th., 2002a. Eine Bewertung von Nutzungsstrategien in Buchenbeständen (*Fagus sylvatica* L.) vor dem Hintergrund des Risikos der Farbkernbildung—eine waldbaulich-forstökonomische Studie (Accepted by the "Wissenschaftszentrum für Ernährung, Landnutzung und Umwelt der Technischen Universität München" as a "Habilitationsschrift").

Knoke, Th., 2002b. Value of complete information on red heartwood formation in beech (*Fagus sylvatica* L.). Silva Fennica 36, 841–851.

Knoke, Th., Schulz Wenderoth, S., 2001. Ein Ansatz zur Beschreibung von Wahrscheinlichkeit und Ausmaß der Farbkernbildung bei Buche (*Fagus sylvatica* L.). Forstw. Cbl. 120, 154–172.

Krutzsch, H., 1952. Waldaufbau. Deutscher Baucrnverlag, Berlin.

Marques, J.C., Jørgensen, S.E., 2002. Three selected ecological observations interpreted in terms of thermodynamic hypothesis. Contribution to a general theoretical framework. Ecol. Model. 158, 213–221.

Möhring, B., 1986. Dynamische Betriebsklassensimulation—Ein Hilfsmittel für die Waldschadensbewertung und Entscheidungsfindung im Forstbetrieb. Berichte des Forschungszentrums Waldökosysteme-Waldsterben der Universität Göttingen Band 20.

Morsing, M., 2001. Simulating Selection System Management of European Beech (*Fagus sylvatica* L.). Ph.D. Thesis. The Royal Veterinary and Agricultural University, Danish Forest and Landscape Research Institute.

Necesany, V., 1969. Forstliche Aspekte bei der Entstehung des Falschkernes bei der Buche. Holz-Zentralblatt 95, 563–564.

Odum, H.T., 2002. Explanation of ecological relationships with energy systems concepts. Ecol. Model. 158, 201–211.

Pretzsch, H., 1999. Waldwachstum im Wandel. Forstw. Cbl. 118, 228–250.

Racz, J., Schulz, H., Knigge, W., 1961. Untersuchungen über das Auftreten des Buchenrotkerns. Der Forst- und Holzwirt 16, 413–417.

Rathke, K.-H., 1996. Zu: Rotkern Bei Buche. Allg. Forstz./Der Wald 51, 1312.

Richter, J., 2001. Buchenrotkern: Vermeiden oder Verwerten? Forst. und Holz. 56, 662–664.

Sachsse, H., 1991. Kerntypen der Rotbuche. Forstarchiv 62, 238–242.

SAS Institute, 1990. SAS/STAT® User's Guide, Version 6, 4th ed., Volume 2. SAS Institute Cary, USA.

Schuemer, R., Ströhlein, G., Gogolok, J., 1990. Datenverarbeitung und statistische Auswertung mit SAS. Band II: Komplexe statistische Analyseverfahren. Fischer, Stuttgart, New York.

Seeling, U., 1992. Abnorme Kernbildung bei Rotbuche (*Fagus sylvatica* L.) und ihr Einfluß auf holzbiologische und holztechnische Kenngrößen. Berichte des Forschungszentrums Waldökosysteme, Reihe A, Band 77.

Seeling, U., 1998. Kerntypen im Holz—Konsequenzen für die Verwertung am Beispiel der Buche (*Fagus sylvatica* L.). Schweiz. Z. Forstwes. 149, 991–1004.

Seeling, U., Becker, G., Schwarz, C., 1999. Stand der Buchenrotkernforschung und zerstörungsfreie Erfassung des Rotkerns bei Buche (*Fagus sylvatica* L.). Institut für Forstbenutzung und Forstliche Arbeitswissenschaft Universität Freiburg. Interner Abschlußbericht.

Spellmann, H., 1999. Überführung als betriebliche Aufgabe. Forst. und Holz. 54, 110–116.

Tarp, P., Helles, F., Holten-Andersen, P., Bo Larsen, J., Strange, N., 2000. Modelling near—natural silvicultural regimes for beech—an economic sensitivity analysis. Forest Ecol. Manage. 130, 187–198.

Trampisch, H.J., 1985. Diskriminanzanalyse. In: Deichsel, G., Trampisch, H.J. (Eds.), Clusteranalyse und Diskriminanzanalyse. Fischer, Stuttgart, New York.

Voß, A., Brandl, H., 1991. Betriebswirtschaftliche Aspekte und Folgerungen zur Farbverkernung bei der Rotbuche in Baden-Württemberg. Mitteilungen der Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg, Heft 158, Teil II.

Weber, E., 1986. Grundriß der biologischen Statistik. 9. Fischer, Auflage. Stuttgart.

Weihs, U., Dubbel, V., Krummheuer, F., Just, A., 1999. Die elektrische Widerstandstomographie—Ein vielversprechendes Verfahren zur Farbkerndiagnose am stehenden Rotbuchenstamm. Forst. und Holz. 54, 166–170.

Wilhelm, G.J., Letter, H.-A., Eder, W., 1999. Konzeption einer naturnahen Erzeugung von starkem Wertholz. Allgem. Forstz./Der Wald 54, 232–240.

Wilhelm, G.J., Letter, H.-A., Eder, W., 2001. Zu: Konzepte zur Buchen-Lichtwuchsdurchforstung. Allgem. Forstz./Der Wald 56, 1226–1227.

Yang, Y., Titus, S.J., Huang, S., 2003. Modelling individual tree mortality for white spruce in Alberta. Ecol. Model. 163, 209–222.

Zell, J., Hanewinkel, M., Seeling, U., 2003. Financial optimisation of target diameter harvest of European beech (*Fagus sylvatica*) considering the risk of decrease of timber quality due to red heartwood. Forest Policy Econ. (submitted for publication).

Ziegler, H., 1968. Biologische Aspekte der Kernholzbildung. Holz als Roh- und Werkstoff 26, 61–68.

Zycha, H., 1948. Über die Kernbildung und verwandte Vorgänge im Holz der Rotbuche. Forstw. Cbl. 67, 80–109.