

Article

## Frequency of False Heartwood of Stems of Poplar Growing on Farmland in Sweden

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**Abstract:** Swedish owners of poplar stands are interested in both the wood quality and the use of poplars that are soon to be harvested. An important concern is the frequency of false heartwood (FHW) in the stems. We have presented an overview of the factors causing discolored wood as well as the industrial use and quality of the end products. We have studied poplar stems growing at 22 sites in Sweden between latitudes 55° N and 60° N. The mean age of the poplar was 23 years (range 14–41), the mean stand density 1011 stems ha<sup>−1</sup> (range 155–3493) and the diameter at breast height (DBH) (over bark) 246 mm (range 121–447). All stands were growing on clay soils (light and medium clay and light clay tills). All of the sampled stems (42) contained false heartwood. At 0%–50% of stem height, all sampled trees were discolored and at 90% of stem height, 33% were discolored. The percentage of false heartwood area by stem area was highest at 1% and 10% of stem height (26.6% and 24.7% respectively). The “FHW” part of the stem had a radius of 47 mm (range 9–93) at 30% of stem height, which corresponds to 50% of the total stem radius. A log of six meters represents about 30% of stem height. Equations describing the correlation between DBH and the diameter of FHW at different stem heights (1%, 10%, 30%, 50%, 70% and 90%) and table describing FHW volume % by total stem volume at the first 50% of stem height were constructed. These might be helpful for estimating the percentage of fresh wood in a stem. However, most of the fast-growing poplars will be harvested as biofuel.

**Keywords:** clone; false heartwood; poplar; soil types

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## 1. Introduction

There has been a general increase in interest in the management of fast-growing broadleaved trees in the Nordic countries (and elsewhere). The earliest trials with poplars in Sweden started with plant material originating from Oregon and Washington, with the aim of breeding material for the Swedish Match Company [1]. Poplar plantations in Sweden are now about 20 years old and their owners have to harvest the stands. In the future short rotation is a promising supply of poplar biomass in Sweden [2]. In Yugoslavia, research on eastern cottonwood (*Populus deltoides* Bartr.) has shown there is a high production of biomass over a short rotation (2–12 years) [3].

However, forest owners and farmers are also interested in managing poplar for pulpwood and, in some cases, timber, despite the lack of suitable climate-adapted clones and uncertainties regarding appropriate management, pest control, economic factors and markets. Poplar stems cut in thinnings have contained discolored wood and the owners are concerned about quality and how frequently this discolored wood occurs.

The wood quality of different broadleaf species is defined according to their “natural” properties including the color of the wood. Mostly, the wood color is uniform from the pith to the cambium. However, for individuals, parts of the wood extending from the pith can be dark (red, brown, grey or black). Darkly colored wood is normal in some species [e.g., elm (*Ulmus* sp.); oak (*Quercus* sp.); sweet chestnut (*Castanea sativa* L.); black walnut (*Juglans regia* L.)] and not classified as false heartwood. Wood discoloration has been reported for some broadleaved species: poplars [4], beech, (*Fagus sylvatica* L.) [5], wild cherry (*Prunus avium* L.) [6], paper birch (*Betula papyrifera* Marsh.) [7], silver birch (*Betula pendula* Roth) [8] and ash (*Fraxinus excelsior* L.) [9].

When describing discoloration found in broadleaf species, there are different names for the phenomenon: affected wood, discolored wood, stained wood, wetwood, wounded wood, black heart, red heart, black heartwood, false heartwood, pathological heartwood, red heartwood *etc.* [10–17]. There is no common name that has been officially accepted in the terminology. Here we use false heartwood (FHW) throughout the paper but, where quoted, we use the name as written in the referenced report.

Information about different types of discoloration and species is presented among others by Hörnfeldt *et al.* [18] who wrote an overview of FHW in beech, birch and ash. Kerr [17] reviewed the occurrence of black heart in ash in relation to management and the influence on timber price and Ward and Pong [19] reported on the available information about wetwood in trees.

Wetwood is a type of false heartwood and appears in aspen and poplar but also in willow (*Salix* sp.) and fir (*Abies* sp.) [20]. What follows below is an overview about FHW or wetwood in poplar stems. True heartwood in aspen and poplar stems, if it exists, is difficult to distinguish in stems without discolored wood. Therefore, false heartwood in poplars is easy to observe. There are no published reports or first-hand experience of the importance and extent of false heartwood in poplar in Sweden. Below follows an overview of the main factors and experiences of this discolored wood, based on international scientific reports and knowledge.

Wetwood is a type of heartwood that has high water content [19]. In a study of balsam poplar (*Populus basamifera* L.) the moisture contents in sapwood was 122 (77–187)% and in wetwood 150 (100–216)% of oven dry weight [21]. In the study pH in wetwood was slightly basic and in sapwood

slightly acidity. A similar result was reported in a study of black poplar (*Populus nigra* L.) [22]. The odor of fresh wetwood indicates anaerobic bacteria activity [19]. According to Wallin [20] bacteria was more frequent in wetwood (92.5% of total isolation) of balsam poplar than in sapwood (54.4%). Poplars with wetwood contain large and diverse populations of bacteria [23]. In a review of discoloration in the wood of living and cut tree species, Bauch [24] concluded that discoloration including wetwood is caused by physiological processes (environmentally initiated), biochemical and chemical reactions.

Studies of the presence of FHW in poplar stems have been reported from different countries. Wang *et al.* [25] reported a distribution of wet wood in all stems of *P. × xiaohei* Hwang and Liang in stands growing in northern China. The heartwood area increased with decreasing stem number per hectare. In a study of 17 Fremont cottonwood (*Populus fremontii* S. Watson) plantations in Arizona, all stands had wetwood symptoms [4]. The percentage stems with wetwood in a stand varied depending on diameter. In the lowest diameter class (diameter at breast height (DBH) 1–32 cm), the percentage ranged from 14% to 80%. On the contrary, the frequency was correlated with stand density where dense stands (1–3 m) had the highest percentage.

According to the presented overview of the literature, discoloration of the wood of broadleaf species is common. From a practical point of view, there are different opinions about the quality of discolored wood in stems. Hiratsuka and Loman [26] concluded, in a review of decay of aspen and balsam poplar in Alberta, that plywood production demands decay-free, high quality logs for veneer. Discolored wood reduces the veneer quality. To reduce the higher moisture content in poplar veneer logs to 5%, it requires 15% more time to dry than spruce. Sachs *et al.* [27] reported that wetwood took two to six times longer to dry than sapwood in order to reach a level of 6%–8% moisture. A similar conclusion about the need for a longer drying period is reported by Boone [28]. Ward and Pong [19] concluded in their overview that wetwood is a cause of losses of wood for the industry. The wood must be dried for 50% longer than fresh wood. Dried board made of wetwood could crack more and develop other quality defects. Control of moisture content in veneer from poplars with wetwood is a technical problem that causes disruption in the processing of veneer. There were no differences in basic density between sapwood and wetwood in balsam poplar [21,29]. However, Ward and Pong [19] reported lower basic density in wetwood than in sapwood. They also reported that boards with wetwood might lower the strength properties.

In Sweden, there is great interest in the management of fast-growing broadleaved species. The demand for information about the wood quality of poplar has increased, as some of the oldest poplar plantations (20–25 years old) are now ready to be harvested. An important factor is false heartwood in poplar stems, which has been observed in thinnings after harvest. The owners want to know about the frequency of FHW in a stand, the formation in the stem, clone dependence, site relationships and influence on wood quality amongst other factors. The pulp industry has asked whether poplar wood is acceptable as pulp wood. As most of the poplar stems have discolored wood, the pulp industry may have objections about the quality and not buy the product. However, a mixture of pulp woods containing poplar with wetwood and sapwood has been shown to produce an acceptable quality of the pulp and paper when processed by pulp mills [25]. Poplar is also an interesting source of material for the pulp industry in former Yugoslavia [3].

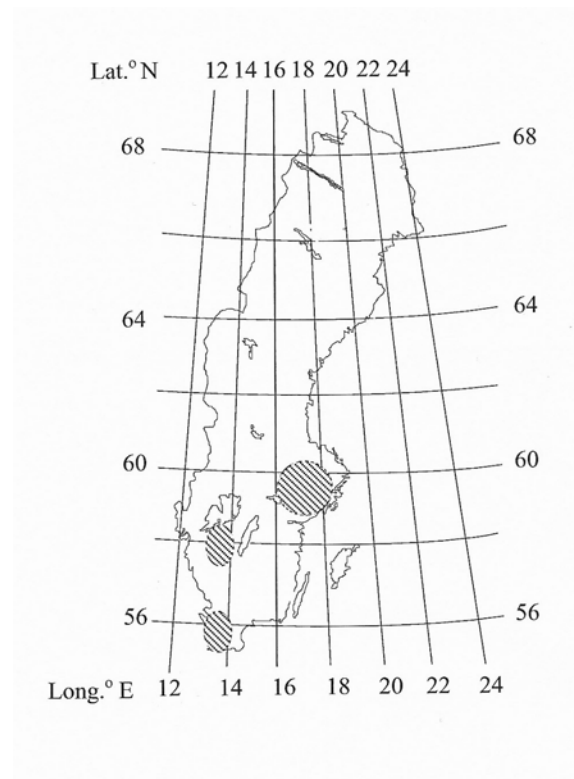
The objectives of this paper are to present the available information about FHW in broadleaved species as a base for understanding the presence of heartwood in poplar stems. We present results from a study of FHW in living poplar stems growing on former farmland in Sweden.

## 2. Materials and Methods

### 2.1. Study Site

Data from 22 sites ranging from 55° N to 60° N and altitudes from 15 to 215 m a.s.l. were used (Figure 1 and Table 1). The stands were planted with bare roots on former farmland, which had been harrowed. Most of the stands were 20 years old or more. The most common planting density was 2000 to 2500 poplars per hectare. Some of the stands have been thinned during the rotation, but some of them were very dense. The diameter of old poplars growing in dense stand without thinning was smaller than in younger stands which were thinned. There was a lack of information about the origin of some of the planted hybrid poplars, but the most frequent in stands were clones of ‘OP-42’ (*Populus maximowiczii* Henry × *P. trichocarpa* Torr. and Gray) (10) and balsam poplar (5). Other poplar varieties found were *P. trichocarpa* (4) and ‘Boelare’ (*P. trichocarpa* × *P. deltoides* Bartr. ex Marshall) (2), Table 2.

**Figure 1.** Locations of the study sites, all on abandoned farmland in Sweden.



**Table 1.** Main characteristics of hybrid poplar stands growing on 22 sites in Sweden.

| Location no.  | Age, years | DBH, mm<br>Mean $\pm$ SE | Height, m      | No. of stems ha <sup>-1</sup> | Basal area m <sup>2</sup> ha <sup>-1</sup> | Soil type        | Variety <sup>1</sup> |
|---------------|------------|--------------------------|----------------|-------------------------------|--------------------------------------------|------------------|----------------------|
| 1             | 18         | 248 $\pm$ 3              | 24.0           | 875                           | 42.3                                       | Light clay       | 2                    |
| 2             | 21         | 330 $\pm$ 5              | 29.2           | 361                           | 30.9                                       | Light clay       |                      |
| 3             | 20         | 277 $\pm$ 4              | 24.5           | 549                           | 33.1                                       | Light clay       | 4                    |
| 4             | 41         | 279 $\pm$ 11             | 22.0           | 1281                          | 78.3                                       | Light clay       | 2                    |
| 5             | 23         | 196 $\pm$ 7              | 22.8           | 632                           | 19.1                                       | Light clay       | 1                    |
| 6             | 34         | 306 $\pm$ 8              | 25.7           | 840                           | 61.8                                       | Light clay       | 1                    |
| 7             | 23         | 186 $\pm$ 5              | 21.2           | 966                           | 26.2                                       | Light clay       | 2                    |
| 8             | 16         | 128 $\pm$ 8              | 20.2           | 3279                          | 42.2                                       | Light clay       | 2                    |
| 9             | 19         | 246 $\pm$ 4              | 28.5           | 1250                          | 59.4                                       | Medium clay      | 2                    |
| 10            | 34         | 291 $\pm$ 8              | 27.2           | 398                           | 26.5                                       | Medium clay      | 1                    |
| 11            | 24         | 293 $\pm$ 3              | 25.9           | 457                           | 30.8                                       | Light clay       | 3                    |
| 12            | 19         | 193 $\pm$ 7              | 14.5           | 1111                          | 32.5                                       | Medium clay      | 3                    |
| 13            | 20         | 182 $\pm$ 7              | 14.6           | 1111                          | 28.9                                       | Medium clay      | 3                    |
| 14            | 20         | 174 $\pm$ 10             | 20.1           | 800                           | 19.0                                       | Medium clay      | 3                    |
| 15            | 23         | 256 $\pm$ 9              | 22.0           | 1005                          | 51.7                                       | Medium clay      | 4                    |
| 16            | 20         | 236 $\pm$ 7              | 22.5           | 1015                          | 44.4                                       | Medium clay      | 1                    |
| 17            | 21         | 186 $\pm$ 7              | 24.6           | 1200                          | 32.6                                       | Light clay       | 3                    |
| 18            | 14         | 121 $\pm$ 5              | 17.8           | 3493                          | 40.2                                       | Light clay       | 2                    |
| 19            | 19         | 283 $\pm$ 9              | 29.1           | 506                           | 31.8                                       | Light clay tills | 2                    |
| 20            | 19         | 280 $\pm$ 4              | 27.6           | 440                           | 27.1                                       | Light clay tills | 2                    |
| 21            | 32         | 447 $\pm$ 11             | 22.1           | 155                           | 24.3                                       | Light clay       | 2                    |
| 22            | 20         | 267 $\pm$ 6              | 24.5           | 520                           | 29.1                                       | Silty tills      | 2                    |
| Mean $\pm$ SD | 23 $\pm$ 7 | 246 $\pm$ 73             | 23.2 $\pm$ 4.1 | 1011 $\pm$ 834                | 36.9 $\pm$ 14.8                            |                  |                      |
| Range         | 14–41      | 121–447                  | 14.5–29.2      | 155–3493                      | 19.0–78.3                                  |                  |                      |

<sup>1</sup> Clones of poplar species: 1. *P. Trichocarpa*; 2. ‘OP-42’ (*P. maximowiczii*  $\times$  *P. Trichocarpa*); 3. *P. balsamifera*; 4. ‘Boelare’ (*P. trichocarpa*  $\times$  *P. deltoides*).

## 2.2. Methods

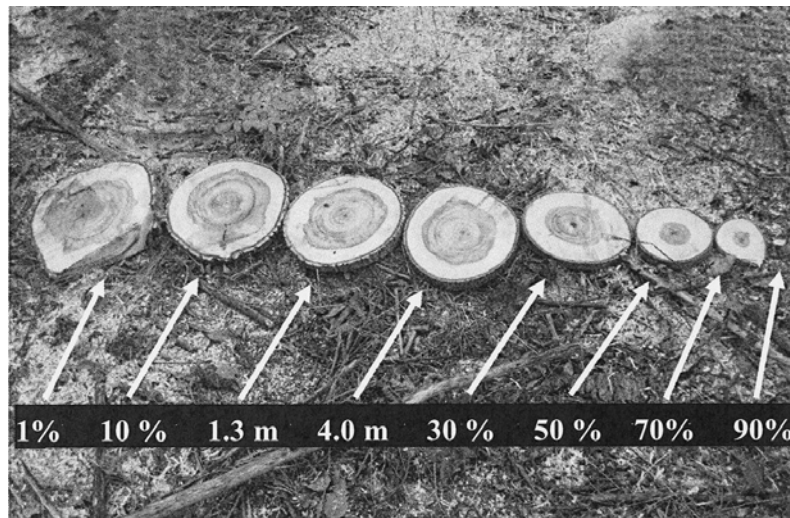
In each stand, one to four sample trees were studied, totaling 42 trees over the whole study (Table 2). Based on the diameter distribution trees with mean diameter, diameter in the upper and lower quartile was chosen. Only one tree with mean diameter was sampled in some stands as the owner did not accept more felled trees. Most of the stands had been used earlier for a study of biomass [2]. The felled stems were examined for visible damage or decay. Disks were cut from the felled stems at 1%, 10%, 30%, 50%, 70% and 90% of tree height and at 1.3 m (DBH) and 4.0 m (Figure 2). In the laboratory, the diameter under bark for the disks and the diameter of false heartwood were measured. The disks were cross-callipered as the pattern of discoloration was irregular. The percentage area of FHW by stem area for all disks at the section heights was calculated. Estimation of total volume and volume of FHW in stems in the first 50% of the stem height was made. The volume of the sections 1.3 m, 10%, 30% and 50% of stem height was calculated by multiplying the stem and FHW area on the middle of each section by the length of the sections and added together.

**Table 2.** Main characteristics of 42 sampled hybrid poplar trees at 22 sites in Sweden.

| Stand no. | Tree no. | Age, years | DBH, mm   | Height, m  | Crown level, m | Soil type        | Variety <sup>1</sup> |
|-----------|----------|------------|-----------|------------|----------------|------------------|----------------------|
| 1         | 1        | 18         | 288       | 25.0       | 10.7           | Light clay       | 2                    |
| 2         | 1        | 21         | 512       | 23.0       | 7.2            | Light clay       |                      |
| 3         | 1        | 20         | 251       | 20.5       | 3.8            | Light clay       | 4                    |
| 4         | 1        | 41         | 442       | 21.3       | 5.6            | Light clay       | 2                    |
| 4         | 2        | 41         | 292       | 22.8       | 6.5            | Light clay       | 2                    |
| 5         | 1        | 23         | 175       | 21.0       | 4.6            | Light clay       | 1                    |
| 5         | 2        | 23         | 266       | 21.3       | 4.9            | Light clay       | 1                    |
| 6         | 1        | 34         | 403       | 25.7       | 9.6            | Light clay       | 1                    |
| 6         | 2        | 34         | 243       | 23.2       | 10.9           | Light clay       | 1                    |
| 7         | 1        | 23         | 245       | 21.6       | 5.9            | Light clay       | 2                    |
| 7         | 2        | 23         | 172       | 21.2       | 5.0            | Light clay       | 2                    |
| 7         | 3        | 23         | 218       | 19.4       | 5.4            | Light clay       | 2                    |
| 8         | 1        | 16         | 145       | 20.2       | 3.9            | Light clay       | 2                    |
| 8         | 2        | 16         | 140       | 18.1       | 5.0            | Light clay       | 2                    |
| 8         | 3        | 16         | 124       | 18.2       | 5.4            | Light clay       | 2                    |
| 8         | 4        | 16         | 170       | 21.1       | 4.0            | Light clay       | 2                    |
| 9         | 1        | 19         | 431       | 26.8       | 7.3            | Medium clay      | 2                    |
| 10        | 1        | 34         | 456       | 32.1       | 14.3           | Medium clay      | 1                    |
| 11        | 1        | 24         | 338       | 24.3       | 7.6            | Light clay       | 3                    |
| 11        | 2        | 24         | 270       | 27.5       | 8.9            | Light clay       | 3                    |
| 12        | 1        | 19         | 227       | 21.4       | 5.0            | Medium clay      | 3                    |
| 12        | 2        | 19         | 195       | 21.0       | 8.6            | Medium clay      | 3                    |
| 13        | 1        | 20         | 237       | 22.4       | 5.1            | Medium clay      | 3                    |
| 13        | 2        | 20         | 185       | 20.4       | 6.1            | Medium clay      | 3                    |
| 14        | 1        | 20         | 234       | 21.8       | 6.8            | Medium clay      | 3                    |
| 14        | 2        | 20         | 189       | 19.9       | 5.5            | Medium clay      | 3                    |
| 15        | 1        | 23         | 269       | 22.7       | 6.6            | Medium clay      | 4                    |
| 15        | 2        | 23         | 203       | 22.3       | 9.8            | Medium clay      | 4                    |
| 16        | 1        | 20         | 235       | 21.5       | 3.7            | Medium clay      | 1                    |
| 16        | 2        | 20         | 258       | 23.4       | 4.8            | Medium clay      | 1                    |
| 17        | 1        | 21         | 439       | 24.0       | 9.7            | Light clay       | 3                    |
| 17        | 2        | 21         | 337       | 25.1       | 13.2           | Light clay       | 3                    |
| 18        | 1        | 14         | 160       | 17.8       | 9.3            | Light clay       | 2                    |
| 18        | 2        | 14         | 147       | 16.7       | 7.9            | Light clay       | 2                    |
| 19        | 1        | 19         | 488       | 28.8       | 6.1            | Light clay tills | 2                    |
| 19        | 2        | 19         | 411       | 30.0       | 12.3           | Light clay tills | 2                    |
| 19        | 3        | 19         | 183       | 22.7       | 10.5           | Light clay tills | 2                    |
| 20        | 1        | 19         | 231       | 25.2       | 9.2            | Light clay tills | 2                    |
| 20        | 2        | 19         | 351       | 27.6       | 8.5            | Light clay tills | 2                    |
| 21        | 1        | 32         | 487       | 21.2       | 5.3            | Light clay       | 2                    |
| 22        | 1        | 20         | 325       | 23.8       | 8.3            | Silty tills      | 2                    |
| 22        | 2        | 20         | 261       | 23.0       | 9.3            | Silty tills      | 2                    |
| Mean ± SD |          | 22 ± 6     | 227 ± 108 | 22.8 ± 3.3 | 7.3 ± 2.7      |                  |                      |
| Range     |          | 14–41      | 124–512   | 16.7–30.0  | 3.7–14.3       |                  |                      |

<sup>1</sup> Clones of poplar species: 1. *P. Trichocarpa*; 2. ‘OP-42’ (*P. maximowiczii* × *P. Trichocarpa*); 3. *P. balsamifera*; 4. ‘Boelare’ (*P. trichocarpa* × *P. deltoides*).

**Figure 2.** Disks from sections at 1%, 10%, 30%, 50%, 70%, 90% of tree height and 1.3 and 4.0 m.



### 2.3. Soil Analysis

In the previously mentioned study by Johansson and Karačić [2], soil types for the stands studied were analyzed. Of all the stands in this study, 13 were growing on light clay soils, 7 on medium clay soils and 2 on till soils (Table 1).

### 2.4. Data Analyses

The percentage false heartwood area by stem diameter under bark representing the stem sections (1%–90%) was calculated. The distribution of false heartwood at different heights (1%–90%) of the stem was calculated on the basis of an equation describing the correlation between DBH and the diameter of the lateral distribution of the heartwood.

Two functions were tested:

$$\text{A linear function } FHW = \beta_0 + \beta_1 \times DBH \quad (1)$$

$$\text{A power function } FHW = \beta_0 \times DBH^{\beta_1} \quad (2)$$

where FHW = diameter of false heartwood, mm; DBH = diameter at breast height, mm;  $\beta_0$  and  $\beta_1$  are parameters.

The power function is frequently used [30,31].

Individual curves for the sections 1%–90% were calculated.

Data were analyzed using analysis of variance (ANOVA) with the GLM procedure using the SAS/STAT system for personal computers [32] to evaluate the differences between clones, soil types and percentage for FHW. The fit of the nonlinear regressions was assessed using the coefficient of determination [33]:

$$R^2 = 1 - [SSE/SST \text{ (No. of observations)}] \quad (3)$$

Where:

$$SSE = \sum_{i=1}^n (w_i - \bar{w}_i)^2$$

and:

$$SST = \frac{1}{n} \sum_{i=1}^n (w_i - \hat{w}_i)^2$$

The quality of the regression was also tested using the root mean squared error (RMSE):

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(w - \hat{w}_i)^2}{n}} \quad (4)$$

where  $w_i$ ,  $\bar{w}_i$  and  $\hat{w}_i$  are the observed, mean and predicted weights ( $w$ ).

Throughout this paper, means are presented together with their associated standard deviation (SD).

### 3. Results and Discussion

#### 3.1. Characteristics of the Distribution of False Heartwood in Stems

In some of the studied stands, only one tree could be sampled according to the owner. The sample is therefore unbalanced and this should be considered when analyzing the results. In our study, false heartwood was found in all studied stems. The percentage of FHW area decreased with increasing stem height. At 0%–30% of stem height, all sampled stems were discolored; at 90% of stem height, 33% were discolored, Table 3.

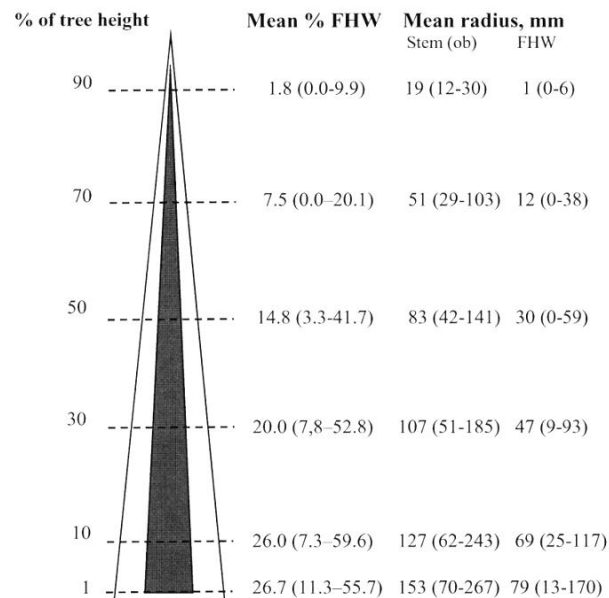
**Table 3.** Percentage stems with false heartwood on different stem sections.

| 1%  | 10% | 30% | 50% | 70% | 90% |
|-----|-----|-----|-----|-----|-----|
| 100 | 100 | 100 | 95  | 81  | 33  |

The percentage of FHW by stem area at different sections was highest at 1% and 10% of stem height (26.1% and 26.0% respectively), Figure 3. About 50% of the radius on the 1% and 10% sections was discolored with 40% on the 30% and 50% sections. The colored part of stems was found at a mean 47 mm (range 9–93 mm) at 30% of stem height, which is about 6 m or one (timber) or two (veneer) logs, Figure 3.

The tested functions (1) and (2) fitted the data for all sections. The curves described by the functions were statistically acceptable although with moderate determination factors for function (1) (Table 4). Function (2) fitted the data best with high determination factors.

**Figure 3.** Mean (range) percentage area of false heartwood area by stem area at 1%–90% of tree height and mean (range) radius, mm, of stem and false heartwood in different sections (1%–90%).



**Table 4.** Estimated parameters of functions (1) and (2) for diameter distribution of false heartwood (FHW), mm by DBH, mm in different stem sections of poplar trees growing on former farmland.

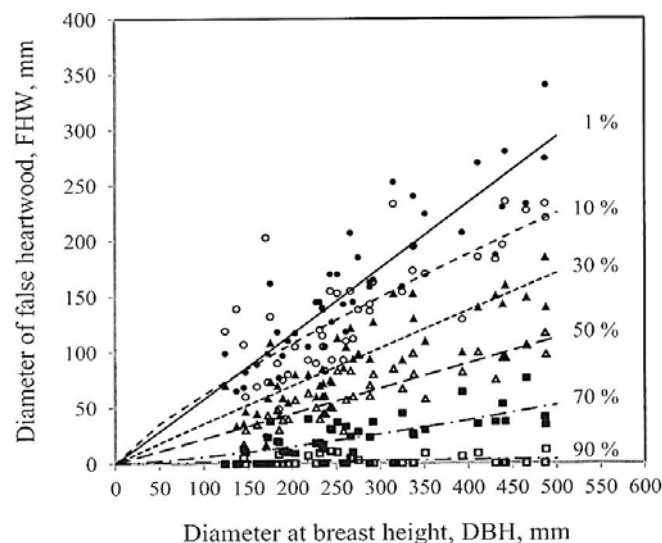
| Components        | Parameter | Parameter estimates | Standard errors of parameters | $R^2$ | RMSE    | Pr > F  |
|-------------------|-----------|---------------------|-------------------------------|-------|---------|---------|
| <i>Function 1</i> |           |                     |                               |       |         |         |
| 1%                | $\beta_0$ | −3.3056             | 2.1435                        | 0.79  | 31.2586 | <0.0001 |
|                   | $\beta_1$ | 0.5954              | 0.0074                        |       |         |         |
| 10%               | $\beta_0$ | 30.2223             | 2.3097                        | 0.59  | 33.6823 | <0.0001 |
|                   | $\beta_1$ | 0.3922              | 0.0515                        |       |         |         |
| 30%               | $\beta_0$ | 0.6907              | 1.3919                        | 0.75  | 20.2978 | <0.0001 |
|                   | $\beta_1$ | 0.3425              | 0.0311                        |       |         |         |
| 50%               | $\beta_0$ | −3.8786             | 1.0905                        | 0.70  | 15.9028 | <0.0001 |
|                   | $\beta_1$ | 0.2371              | 0.0037                        |       |         |         |
| 70%               | $\beta_0$ | −8.6974             | 0.9339                        | 0.45  | 13.6198 | <0.0001 |
|                   | $\beta_1$ | 0.1188              | 0.0032                        |       |         |         |
| 90%               | $\beta_0$ | 1.1242              | 0.2780                        | 0.02  | 4.0548  | <0.0001 |
|                   | $\beta_1$ | 0.0054              | 0.0010                        |       |         |         |

Table 4. Cont.

| Components | Parameter | Parameter estimates | Standard errors of parameters | $R^2$ | RMSE    | Pr > F  |
|------------|-----------|---------------------|-------------------------------|-------|---------|---------|
| Function 2 |           |                     |                               |       |         |         |
| 1%         | $\beta_0$ | 0.5532              | 0.0422                        | 0.97  | 31.2730 | <0.0001 |
|            | $\beta_1$ | 1.0095              | 0.0131                        |       |         |         |
| 10%        | $\beta_0$ | 1.5461              | 0.1458                        | 0.95  | 19.2008 | <0.0001 |
|            | $\beta_1$ | 0.8012              | 0.0164                        |       |         |         |
| 30%        | $\beta_0$ | 0.3959              | 0.0329                        | 0.96  | 20.2731 | <0.0001 |
|            | $\beta_1$ | 0.9761              | 0.0144                        |       |         |         |
| 50%        | $\beta_0$ | 0.2126              | 0.0215                        | 0.94  | 15.9593 | <0.0001 |
|            | $\beta_1$ | 1.0094              | 0.0175                        |       |         |         |
| 70%        | $\beta_0$ | 0.0117              | 0.0027                        | 0.80  | 13.6198 | <0.0001 |
|            | $\beta_1$ | 1.3520              | 0.0397                        |       |         |         |
| 90%        | $\beta_0$ | 0.1174              | 0.0677                        | 0.31  | 4.0431  | <0.0001 |
|            | $\beta_1$ | 0.5558              | 0.1012                        |       |         |         |

The equations constructed expressing the correlation between breast height diameter and the false heartwood area at different stem heights might be used as a tool for indicating the level of the quantity of sapwood in the stems (Figure 4). In the most valuable part of the stem, the lower 50% of stem height, FHW was found in all stems and at 90%, 33% were discolored. As we were not allowed to check all stems in our studied stands, we do not have information about the frequency of discolored stems per stand. Wang *et al.* [25] studied *Populus xiaohei* and reported discolored wood in all studied stems with a decreasing discolored area with increasing stem height. Hofstra *et al.* [4] found in a study of Fremont poplar (*Populus fremontii* S. Watson) in Arizona that there was discolored wood in all of 17 of the stands studied.

**Figure 4.** The relationship between diameter, mm, of false heartwood (FHW) in relation to diameter at breast height (DBH; mm) at 1% (●—), 10% (○--), 30% (▲.....), 50% (△--), 70% (■—) and 90% (□—) of tree height for poplar.



There were no significant differences between clones or soil types and percentage FHW area at DBH (Table 5). Furthermore, there were no interactions between soil types and clones.

**Table 5.** Test of differences between clones, soil types and percentage FHW area at DBH, % and between DBH and percentage FHW area and stem number and percentage FHW area of poplar stems (analysis of variance).

| Source of variation | Degree of freedom | F    | P      |
|---------------------|-------------------|------|--------|
| A (Clones)          | 3                 | 0.37 | 0.7725 |
| B (Soil types)      | 2                 | 0.08 | 0.9224 |
| AxB                 | 3                 | 0.37 | 0.7753 |
| Error               | 40                |      |        |
| Total               |                   |      |        |
| DBH                 | 23                | 1.35 | 0.2614 |
| Error               | 19                |      |        |
| Total               | 42                |      |        |
| Stem number         | 23                | 1.15 | 0.3883 |
| Error               | 19                |      |        |
| Total               | 42                |      |        |

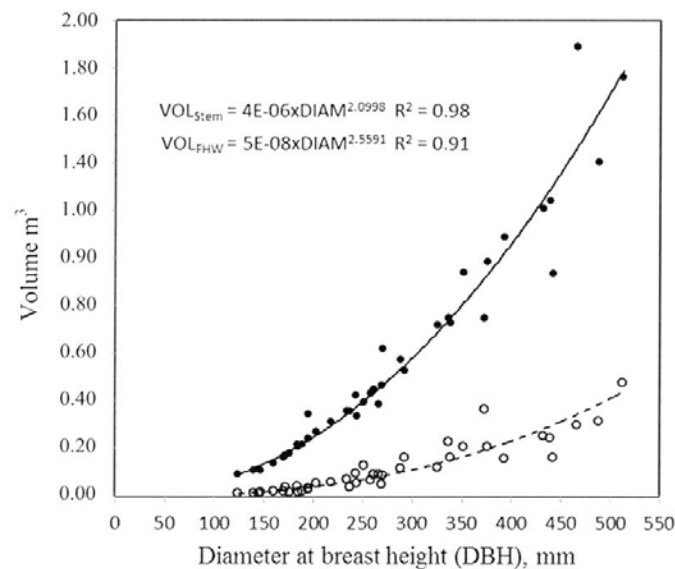
The total volume of sapwood and FHW for 50% of stem height in the studied stands is shown in Figure 5. In a study of stem volume of individual poplar stems 84 (75–89)% of stem volume was found in the first 50% of stem height [34]. In a previous study a test of the precision of volume estimation based on different section length showed that 3 m long section had a deviation of 2% of true volume [34]. Our estimations are an attempt to present a rough overview of the percentage FHW in the commercial part of poplar stems. In a study of *Populus xiaohei* planted in spacings:  $2 \times 5$ ,  $4 \times 5$  and  $4 \times 10$  m 84%–89% of wetwood volume was accumulated in the first 10 m of the poplar height [30]. The percentage FHW volume increased with increasing DBH, Table 6.

In our study an analysis of the percentage of FHW stem area at breast height within diameter classes at breast height shows that the percentage by stems <200 mm was lower than for stems >200 mm, Figure 6. In a study of Fremont poplar, the frequency of discolored wood varied between sites and diameter classes [4]. The frequency of discolored stems increased with increasing DBH. In the smallest diameter class, 0–32 cm, about 45% of the stems were discolored; this increased to 90% in diameter class 33–64 and then 100% in classes up to 161–192 cm.

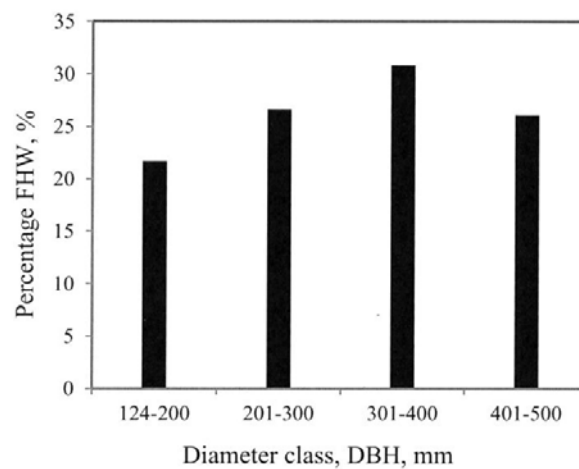
**Table 6.** Percentage FHW volume by total volume in the first 50% of stem height.

|                       | Diameter at breast height, mm |      |      |      |      |      |      |      |
|-----------------------|-------------------------------|------|------|------|------|------|------|------|
|                       | 150                           | 200  | 250  | 300  | 350  | 400  | 450  | 500  |
| % FHW by total volume | 12.5                          | 14.2 | 15.8 | 17.2 | 18.4 | 19.6 | 20.7 | 21.7 |

**Figure 5.** Total volume (●—) and volume of FHW (○- -), m<sup>3</sup>, in the first 50% of stem height for poplar.



**Figure 6.** The percentage FHW area for different DBH.



In our study, there were no significant differences between stem number per hectare or clones and the percentage FHW area at DBH, Table 5. As most of the studied stands were planted with  $\geq 2000$  stems per hectare, with no or sparse thinning, the main reason for the high frequency of FHW must be due to factors other than density. However, there have been no practical examples reported. The frequency of discolored wood and stem number has been studied on *Populus xiaohei* by Jiang *et al.* [35]. In their studies, the proportion of wetwood at DBH increased from 60% to 68.1% in stands with 1000 and 250 stems ha<sup>-1</sup> respectively. Similar results for the same species were presented by Wang *et al.* [25] in a study where the poplars were planted in spacings of  $2 \times 5$ ,  $4 \times 5$  and  $4 \times 10$  m wetwood represented 56%, 62% and 65% of total volume respectively. In a study of six hybrid poplar clones, Garret *et al.* [36] found different percentages of discolored wood *versus* stem diameter in logs.

They stated that there was a possibility of rating clones on the basis of their potential for developing discolored wood.

## 5. Conclusions

This study has focused on the frequency of false heartwood in poplar stems. No studies on this phenomenon for poplars growing in Sweden have been described before.

There was FHW in all studied poplars. Only a few stems per stand could be felled and examined. In all studied stems, FHW was found in stem from sections at 1%, 10% and 30% of stem height.

As the variability of FHW dimensions is high the constructed function expressing the diameter of FHW for different stem heights, %, at different DBH is only a tool indicating the amount of FHW at different stem diameters. In a table the percentage FHW volume by total volume in the first 50% of stem height indicates an increasing FHW volume by increasing DBH.

Up to 50% of the radius at 30% of stem height was sapwood without FHW and might be used for veneer production. According to reports in the literature review poplar stems with FHW might be used as pulp wood. There are some doubts about the quality of poplar boards with wetwood. No reports have, to our knowledge been presented about disadvantages when using the stems with FHW as raw material for bioenergy.

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## Conflict of Interest

The authors declare no conflict of interest.

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