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Compression wood formation and pith eccentricity in *Picea abies* L. depending on selected site-related factors: Detection of compression wood by its spectral properties in reflected light

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Introduction

Studies have shown that the formation of compression wood is a negative gravitropic reaction of the coniferous tree. It is interpreted as serving the tree in recovering from a displacement in order to regain its original orientation in space. For the stem this would be the vertical orientation which it can hardly regain. The observed correction is often limited to the apical meristem leading to the appearance of a sweep. Therefore, compression wood formation can be considered as being a reaction to an external stress which is putting a strain on the tree. A profound knowledge of compression wood distribution could lead to a better understanding of the interaction of ecological factors and the growth or reaction of trees in response to them.
In this study the effects of potential external factors on displacement and consequently compression wood formation are investigated. Trees from sites with different slopes and exposure to the prevailing wind directions are examined for their compression wood distribution and eccentric radial increment using a new hyperspectral image analysis method. The compression wood distribution in stems of Norway spruce is described and the detection of an inter-annual time series in the formation of compression wood is analysed.

Material

One of the objectives of this study is to describe the distribution of the compression wood in the stem of Norway spruce (*Picea abies* [L.] Karst.) and to examine the possible impacts of slope and exposure to the prevailing wind direction on the compression wood formation. Therefore the sites were selected to be as similar as possible, differing only in slope and exposure. In total, trees from five sites were sampled, all of which are located in south-western Germany in the growth region “Black Forest” and “Baar-Wutach”. The sites belong to the submontane to highmontane altitudinal, there climate is suitable for Norway spruce.
One of the sites is almost level with a slope of 1°. Two sites could be said to be strongly inclined with slopes of 10° and 17°, whereas the last two sites with 25° and 29° are considered steep. Of the two pairs of sites on the inclined slopes, one site on each is exposed to the south-west, against the prevailing wind direction, and the other to the north-east. Summarised data for the description of the five different sites are listed in Table 1. The wind data are taken from measurement stations of the DWD - German Weather Service and

the LfU - Landesanstalt für Umweltschutz Baden-Württemberg named in Table 1. Note that the indicated wind directions are where the wind is blowing from in contrast to the aspect of the slope. “Feldberg” is the closest station to the site at Titisee-Neustadt, but due to its exposed situation in the landscape on top of the highest mountain of the Black Forest, the mean wind speed is presumably much higher than that at the site located at an elevation 400 m further down.

Altogether 56 Norway spruce trees were sampled from the stands on the five different sites. All the stands were mature and at least dominated by Norway spruce. The trees belong to the social classes I to III according to KRAFT (pre-dominant to co-dominant). From every sample tree, on average 8.57 cross sectional discs were cut for compression wood analysis, with the north direction marked. The minimum number of discs per sample tree was 5, the maximum 13, from defined heights along the stem. The total number of sample discs taken is over 500 including those for age analysis at a height of 0.3 m.

Table 1: Summarized data for the description of the five sample sites.

Forest district	Waldkirch	Titisee-Neustadt	Bonndorf	Elzach	St. Märgen
Growth region	Black Forest		Baar-Wutach	Black Forest	
Location (Lat./Long.)	48°4' / 8°2'	47°54' / 8°4'	47°49' / 8°16'	48°10' / 8°7'	48°2' / 7°59'
Elevation [m]	1100	1100	960	760	540
Slope [°]	10	17	1	29	25
Aspect	north-east (45°)	south-west (243°)	east (68°)	west (234°)	north-east (27°)
Soil type	humous Cambrisol	Cambrisol	Cambrisol, partly Planosols	Cambisol and Spodo-Dystric Cambisol	Cambrisol
Mean annual temperature [°C]	6.9	5.6	6.1	7	6.9
Mean annual precipitation [mm]	1736	1406	1306	1741	1736
Prevailing-/ mean wind-/ mean storm direction [°] (station)	240 / 251 / 237 Schauinsland	240 / 230 / 223 Feldberg	270 / 293 / 273 Höchenschwand	240 / 247 / 240 Elzach	120 / 162 / 270 Glottertal
Mean annual wind speed [m/sec.]	3.0	7.8	2.1	3.5	2.0

Method

Detection of Compression Wood by its Spectral Properties in Reflected Light

One of the most, if not the most, important issues when describing compression wood distribution is the method used to detect this tissue and to discriminate it from other wood features occurring on stem cross sections. After having tested different approaches to identify a suitable method for the detection of compression wood in dried stem discs from Norway spruce, and to classify it against other wood tissues, it was decided to use hyperspectral image analysis. For the assessment of the cross sections from the stems a method has been developed using the reflected light in the wavelength range 400 – 1000 nm, integrated to 121 bands with a spatial resolution of 0.1 mm, to distinguish compression wood from other wood tissues by its spectral properties. These properties are given by the chemical composition and the scene geometry of the hyperspectral scanner developed for analysis. Hyperspectral image analysis allows for the comparison of the obtained spectra from the cross sections with reference spectra obtained from reference areas. Seven stem cross sections from previously sampled Norway spruce material are classified by cellular properties using light microscopy into the agreed classification system of compression wood severity grades “severe” and “mild” which serve as reference material. The criteria for the grading of compression wood tracheids to normal wood tracheids in the middle of tree rings have been chosen according to Yumoto, M. et al. (1983) but have been slightly modified (Table 2). The tracheids have to exhibit a very thick cell wall, a nearly circular boundary between S1 and S2 and the presence of intercellular spaces to be classified as “severe compression wood”. For “mild compression wood” the cell wall thickness has to be relatively thick, the boundary has to be round but was allowed to be variable depending on the presence or absence of intercellular spaces.

Table 2: Criteria of tracheid classification in cross sections. Criteria of gradation of compression wood tracheids to normal tracheids in the middle of tree rings modified according to YUMOTO, M. et al. (1983).

Criterion (cellular level)	**Compression Wood severe**	**Compression Wood moderate**	**Normal Wood**
Spiral grooves	distinct	poorly developed to absent	absent
Cell wall thickness	very thick	thicker than normal	normal
Cell outline between S1 and S2(L)	round, almost circular	round but variable depending on the presence of intercellular spaces	“rounded rectangles”
Intercellular spaces	generally present	incidentally present	absent
Color appearance	“reddish”	“darker brownish”	“brownish”

The classified areas from these seven discs were used as reference material to calibrate the classification model in order to facilitate the semi-automatic assessment of compression wood content in sample discs using hyperspectral image analysis. These regions were hyperspectrally scanned and 74 mean standardised reference spectra were recorded. These reference spectra, stored in a spectral library, serve in the classification model to discriminate between different wood features based on their spectral properties in reflected light using the “Spectral Angle Mapper” (SAM) classification algorithm (Kruse, F.A. et al. 1993). The algorithm determines the similarity between two spectra by calculating the “spectral angle” between them, treating them as vectors in a space with dimensionality equal to the number of bands. The result is a classification image which shows the best match at each pixel. For breaking down the classification information to the compression wood content of a single growth ring, an extracted grey scale image from the calibrated hyperspectral image, representing a spatial x/y-scanning in a specific wavelength band (435 nm) in the blue part of the Visible Light, is to be read into the growth ring analysis programme previously developed at the Institute for Forest Growth. The semi-automatic measurement of the annual radial increment is adjusted to the spatial resolution of the hyperspectral images and the growth ring boundaries are located. Furthermore, the classification image is interpreted and the two compression wood classes and a third "non-compression wood" class are distinguished. Knowing the growth ring boundaries, it is now possible to break down the overall classification result of a radius into single year patterns of compression wood content by counting the corresponding pixels within a sampling kernel. Aside from recording the compression wood distribution, the annual radial increment is measured in eight radii oriented to the compass directions. An extensive description of the method is given in an submitted article to the IAWA-Journal.

Modelling the Compression Wood Distribution and the Pith Eccentricity

Every stem cross section was scanned in eight radii oriented from the pith to the bark according to the main and auxiliary compass directions. Within each radius the annual increment was measured and the annual compression wood recorded. This sampling design allows the compression wood distribution in the stem cross section in two dimensions (radial and tangential) to be described and, by interpolating the values between the different discs taken from the stem, the third axial dimension can be added. Furthermore, an inter-annual time series of the compression wood formation can be analysed. The classification results and the data from the measurements of the radial annual increment are used to calculate a vector $(\theta|r)$ for the compression wood and growth ring structure of every tree ring. These vectors indicate by their angle (θ) the compass direction of the compression wood distribution or the pith eccentricity. The value for the length (r) gives a gauge to judge the amount of compression wood or the deviation of the pith eccentricity from a concentric circle. These "tree ring vectors" arise from adding the results, which could also be regarded as vectors, of a given tree ring from the eight individual radii scanned from a stem cross section. Adding up the "tree ring vectors" of one stem cross section results in a "disc vector" indicating accurately the amount and the mean direction $(\bar{\theta})$ of compression wood and pith eccentricity. If the resultant vector length (r) is divided by the number of vectors contributing to it, the mean resultant length $(\bar{r})$ results, which is associated with the mean direction $(\bar{\theta})$. The mean resultant length lies in the range (0,1) with interesting properties at the extremes. Further corresponding statistical methods for summary description and analysis of circular data are described by Fisher, N.I. (1993). The Rayleigh test is used to test randomness against an unimodal distribution of the directions for compression wood and pith eccentricity.

Results

Classification of Compression Wood

The method developed to detect compression wood in the reflected light by hyperspectral image analysis was validated by scanning a randomly selected test radius which had not been used for building up the spectral library. A confusion matrix for microscopically identified test areas was calculated and revealed an overall accuracy of >91%. This accuracy was achieved after applying the spatial filter "Majority Analysis" to the classification image thereby homogenizing spurious pixels within a large single class. As can be seen in Figure 1, some errors in the automatic detection occurred in the pith and on the inner side walls of cracks which are judged in part to belong to severe (CWs) or moderate (CWm) compression wood. Such clear misclassifications can be corrected manually in the data files. It is obvious that this would further improve the error statements leading to an overall accuracy of about 96%.

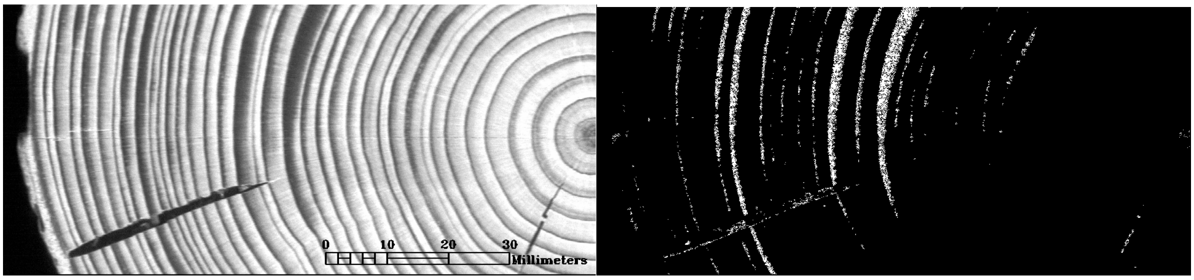

Figure 1: Cross section of a randomly chosen Norway spruce test radius and the corresponding classification result. The radius is extracted from an image cube giving spatial information at wavelength 435 nm in the left part of the image. The right part gives the corresponding classification result in a grey scale image: "Compression Wood severe"--white, "Compression Wood moderate"--grey, "Normal Wood" and "Background/Crack"--black.

Compression Wood Distribution and Pith Eccentricity

At first glance the occurrence of compression wood appears to form half-moon like patterns within tree rings in stem cross sections. The frequency of the compression wood formation is recorded and the extent to which the compression wood extends in the tangential direction within a tree ring is assessed. This is analyzed in the discs from all sample trees of the absolute tree height 1.3 m. The tree rings are subdivided into cambial age classes of 20 years, whereby the innermost tree ring comprising of the pith is excluded. First, it is observed whether compression wood occurs in a tree ring with a certainty of 99%, then it is recorded in how many radii, up to a maximum of eight, the compression wood is formed. On the stem cross sectional level it has been found that the frequency of compression wood formation in a tree ring increases from juvenile to adult wood. The observed frequency distribution of the compression wood formation in the cross sections from a height of 1.3 m for cambial age classes each comprising of 20 years is for class I – 27 %; III – 54 %, V – 57 %; VII – 59 %, IX – 64 %, XI – 61 % and for class XIII – 68 %. For cambial age class I, 87.93% of the segments containing compression wood are limited to a maximum of 135°, whereas in class XIII only 51.99% are limited to this maximum tangential spread. However, the sector containing compression wood can exceed 315° in some tree rings. In the cambial age class XIII this is the case in almost 4% of the tree rings in which compression wood is formed.

A very close relationship is observed between the direction of the compression wood sector in a ring and the direction of its eccentric growth. In 62% of the observations the difference between both directions is within a maximum of 45°. As is shown in Figure 2, both the sectors are oriented towards the north-eastern half of the circle in 79% of the growth rings.

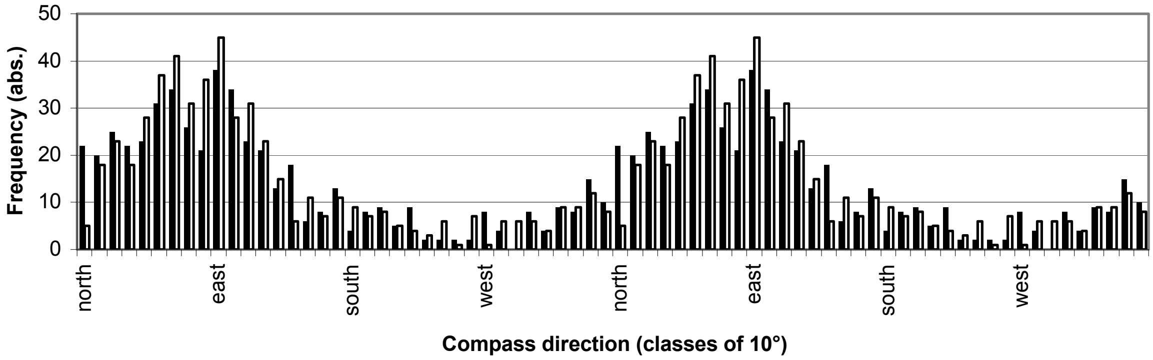

Figure 2: Frequency of the direction of compression wood formation and pith eccentricity in stem cross sections. Compression wood – black columns; pith eccentricity – white columns.

The results of the Rayleigh test of randomness compared to an unimodal distribution reveal highly significant differences in uniformity in the directions of compression wood formation and pith eccentricity at all sites except St. Märgen. The mean directions ($\bar{\theta}$) and the resultant length ($\bar{r}$) for compression wood and pith eccentricity are summarized in Table 3. Almost all mean directions are located in the north (0°) - eastern (90°) part of the circle. They do not follow the direction of the slope of the site, but in most sites the leeward direction of the prevailing wind is within the 95 % confidence interval of the mean directions (CW and IR). This finding is in contradiction to the hypothesis that the exposure of the slope has a decisive effect on the direction of the compression wood formation.
In order to examine the possible effect of exposure to the prevailing wind direction of the site on the formation of compression wood, inter-annual time series of the compression wood formation for the five stands were analysed for identical one year trends in their curves between the sites. The relative mean amount of compression wood formed in the five sites is shown over the calendar year in Figure 3. The bold curve high up indicates how many sites show a simultaneous deviation in the formation of compression wood compared to the previous year.

*Table 3: Summary statistics of the directions for compression wood (CW) and pith eccentricity (IR) of stem cross sections.**Prevailing wind direction$_{(lee)}$ within confident interval; *prevailing wind direction$_{(lee)}$ less then 20° away from the mean direction.*

Summary statistic	Waldkirch	Titisee-Neustadt	Bonndorf	Elzach	St. Märgen
Mean direction $(\bar{\theta})$ **CW**	**66,7°**	**78,2°**	**100,0°**	**48,3°**	**3,5°**
Mean resultant length $(\bar{r})$ **CW**	0,63	0,79	0,82	0,84	0,14
Confidence interval$_{(0.95)}$[°]	52,7 – 80,8**	68,0 – 88,5*	93,2 – 106,7*	41,1 – 55,6*	303,0 – 63,9
Mean direction $(\bar{\theta})$ **IR**	**40,9°**	**69,3°**	**88,1°**	**60,4°**	**237,5°**
Mean resultant length $(\bar{r})$ **IR**	0,72	0,91	0,85	0,80	0,21
Confidence interval$_{(0.95)}$ [°]	29,5 – 52,4*	62,4 – 76,1**	81,9 – 94,4**	53,3 – 67,5**	193,8 – 281,1

It is remarkable that in several years all curves of the mean amount of annual compression wood show an increase compared to the previous year. Where the data are limited to only four sites due to the younger age of the trees in St. Märgen the bold curve is in grey. Hartig, R. (1896) was presumably one of the first to mention that compression wood is formed under the influence of wind. Pillow, M.Y. (1931) relates the sudden increase in the amount of compression wood formed in pine trees in Florida to the occurrence of a hurricane. In the consecutive years he reports a declining amount of compression wood. For the south-western part of Germany, Abetz, P. & Künstle, E. (1982) were able to identify a correlation between the occurrence of compression wood and the amount of incidental harvested wood due to storm and snow damage. In Figure 3 events with an extremely high wind speed are indicated by black columns (Dec. 1927, Nov. 1930, Mar. 1940, Jan. 1955, Mar. 1966, spring 1967, Mar. 1990, Dec. 1999), the grey columns mark major snow damage events (Apr. 1936, Feb. 1958, Apr. 1973); source: a.o. (Volk K. 1968). All these events lead to an increase in the annual mean relative amount of compression wood in the following vegetation period compared to the previous. There is only one exception, the storm in Jan. 1955, after which the amount did not increase before 1956. If the level of the different curves is examined, it is apparent that the trees from the nearly level site at Bonndorf formed the highest mounts of compression wood, followed by those from the steep site exposed to the west in Elzach. The levels of the trees from the sites located in the high montane range close to Waldkirch and Titisee-Neustadt are very similar to each other at a relative low level. The smallest amounts of compression wood are formed in the steep submontane site, exposed to the north-east close to St. Märgen.

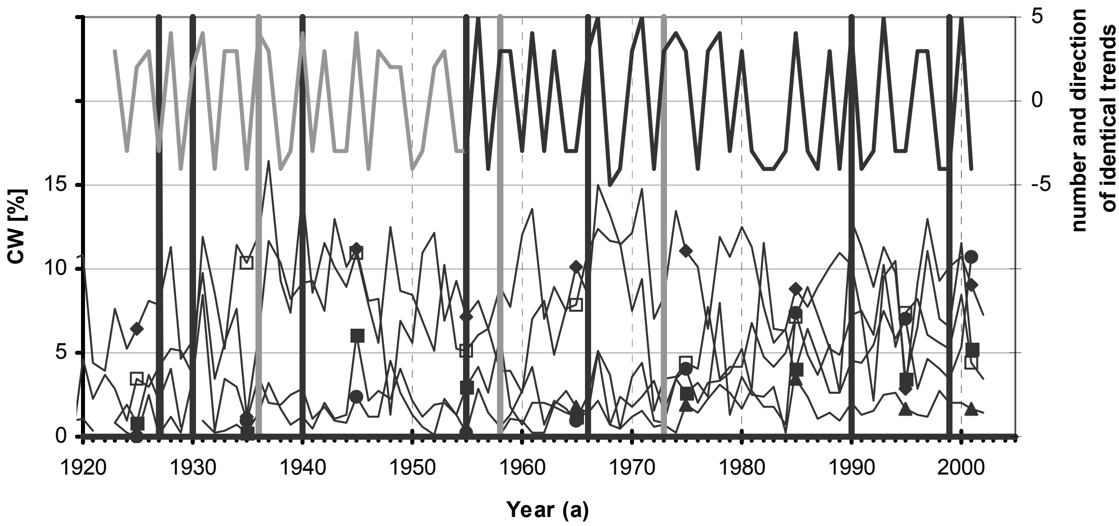

Figure 3: The relative amount of compression wood formation in the calendar years for the five different sites. The black columns indicate years with extremely high wind speed events, the grey ones indicate years with major snow damages. The curve high up shows how many sites display a identical deviation in the amount of compression wood compared to that of the previous year (— 4, — 5 observations). ◆Bonndorf; □Elzach; ▲St. Märgen; ●Titisee-Neustadt; ■Waldkirch.

Discussion

The description of the compression wood distribution allows for relationships of its formation with environmental factors to be analysed. The inter-annual time series of the mean relative amount of Compression wood revealed several years in which in all five sites an increase in relation to the amount of the previous year is observed. These years correlate very well with events of high wind speeds or major damages due to heavy snow loads. A comparison of the mean direction of the compression wood formation with the eccentric radial growths indicates that the prevailing wind direction and the direction where the storms came from explain well the direction of the displacement of the trees and resulting compression wood formation. In contrast, the slope is not able to serve as an explanatory factor. This statement has to be limited to the examined sites. In other altitudinal ranges with higher snow cover and corresponding snow movement processes when melting, it is to be expected that the trees would show pistol butted growth and corresponding compression wood formation. This has not been the case with the sampled trees. High amounts of compression wood occur in the almost level as well as in the steep western exposed sites, whereas the trees of the steep northeast exposed site have the smallest amounts. However, if the exposure to the prevailing wind direction is taken into account, it fits well that the trees at the lower part of the steep northeast exposed site, which are protected from the wind, hardly form compression wood. The trees of the strongly inclined highmontane sites have presumably well adapted over time to the higher wind speeds. Consequently, they form less compression wood after storm events. There still remains the question why the trees from the almost level site have formed the highest amounts of compression wood. The explanation might possibly be found in the ground. The soil consists partly of sandy loam which holds the moisture well and reduces the anchorage of the trees after high precipitations thereby increasing their susceptibility to displacements.

Conclusions

The examination of stem cross sections with the new developed method to detect compression wood in the reflected light by hyperspectral image analysis allows for a three-dimensional description of the compression wood distribution in stems. Together with the compression wood assessment, the annual radial increment was measured, enabling the tree ring structure for eccentric growth to be analysed. The time series analysis of the mean relative amount of compression wood revealed a distinct effect of extremely high wind speed events and heavy wet snow loads on the formation of compression wood. This caused, within several years, the trees of all five sites to increase the amount of compression wood in relation to the year previous to the event. It was not possible to prove that the slope had an effect on the formation of compression wood nor on pith eccentricity, neither with regard to the amount nor to the direction. The directions are in fact dominated by the exposure of the site to the prevailing wind direction.

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