Assessing the vertical distribution and visibility of rockfall scars in trees *(reviewed paper)*

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Abstract: As rockfall consists of falling, bouncing or rolling rocks, impacts on trees occur almost anywhere between ground and several meters above. This paper therefore focuses on 307 discs from three trees to assess the vertical distribution and the visibility of scars on stem surfaces. Results show that scars can be observed at heights of up to nine meters and that signs of past rockfall activity are no longer visible in up to 49% of cases.

Abstract: Steinschläge durch fallende, springende oder rollende Steine können Bäume praktisch überall von Bodennähe bis in mehreren Metern Höhe treffen. Im Aufsatz werden die vertikale Verteilung der Baumschäden sowie die Sichtbarkeit der Verletzungen auf den Stammoberflächen anhand von 307 Stammscheiben untersucht. Als Ergebnis zeigte sich, dass Steinschlagschäden bis in Höhen von neun Metern vorkommen und bis zu 49% der älteren Aufschlagspuren nicht mehr sichtbar sind.

1. Introduction

Rockfall represents a deplacement of individual and superficial rock fragments from cliff faces (Selby 1993) and generally involves volumes < 5 m^3 (Berger *et al.* 2002). As a consequence, single rockfall fragments may only cause damage to those trees standing in the trajectory of rocks (Ø < 50 cm) and boulders (Ø > 50 cm). In addition, rockfall also differs from other processes, such as debris flows, flooding or wet snow avalanches, owing to the presence of different modes of motion and rotation occurring at once, namely falling, bouncing and rolling. As a result, and in opposition to the «flow» processes mentioned above, rockfall fragments hitting trees may cause impacts at considerably varying vertical positions on the stem surface.

Quantitative information on the vertical distribution of rockfall impacts on trees remains rather scarce. Gsteiger (1993) assessed the vertical distribution of scars on seven adult trees at Brienzergrat (Bernese pre-alpine region, Switzerland), but he limited his analysis to only a few stem discs (cross-sections) and the two meters above the ground. Perret *et al.* (2004), by contrast, analyzed the stem surface of 157 trees at Diemtigtal (Bernese pre-alpine region, Switzerland) and documented more than 1700 visible scars. The study did not, however, take into account that older or relatively small injuries might no longer be visible on the stem surface, thus ignoring a certain number of past impacts. Last but not least, Rickli *et al.* (2004) gave an overview on maximum bounce heights for different size classes of rockfall fragments. Results were given for slopes with a gradient of 35° and based on a rather small amount of field data. In addition, Rickli *et al.* (2004) considered neither the influence of neighboring trees nor changes in the slope gradient. As a consequence, the above-cited studies on impact heights of rocks and boulders on trees may give a reasonable first impression on the vertical distribution of scars on stems, but lack detail and do not include hidden (i.e. invisible) scars.

This study therefore aims to analyze the vertical distribution of past rockfall impacts (scars) and estimate the number of visible scars on the surface of the stem using a large number of cross-sections (i.e. stem discs) from adult trees. In order to achieve these goals, three adult trees (*Abies alba* Mill., *Fagus sylvatica* L., *Picea abies* (L.) Karsten) were analyzed from the basal area of the stem to the crown with a total of 307 cross-sections. Results illustrate the large array of impact heights occurring in trees from the protection forest above Altdorf (Bannwald of Altdorf, Canton Uri, pre-alpine region of Switzerland), and they also give us a good idea of how much evidence of past rockfall events remains visible on the stem surface.

2. Study site

The Bannwald of Altdorf is located NNE of the village of Altdorf (Uri, Switzerland), extends from an altitude of 440 m to 1600 m a.s.l., and covers more than 300 hectares (Annen & Redmann 1993). Mean slope gradients in the forest average 70 to 80% and stands consists mainly of *Fagus sylvatica* on the lower parts of the slope (< 1200 m a.s.l.), while *Picea abies* predominates in the sub-alpine zone, which is locally shifted to elevations above 1600 m a.s.l. by the presence of frequent foehn winds. In addition, the local dry soils covering bedrock and exposed cliffs favor colonization with *Pinus sylvestris* L.

Bedrock on the slope is part of the Schächental Flysch unit, forming a compilation of sandstone and clay layers (Labhart 1998). Rockfall is frequently triggered from these heavily fissured formations. Individual rockfall fragments are generally quite small, but boulders of up to 10 m^3 (> 30 tons) have been observed as well. On 16 August 1973, rockfalls even triggered 8000 m^3 from the 100 m high cliff at «Rot Flue» (Niederberger 2002). Evidence of other large rockfalls can be identified in the field and in local chronicles, indicating that major activity took place in 1268 and 1886. The latter event would have caused severe damage to the church and adjacent buildings in the valley floor (Annen & Redmann 1993). Today, rockfall is most frequently triggered from the rock cliff at «Rot Flue», but other source areas exist on the slope as well. Niederberger (2002) indicates that rockfall activity would be favored locally by frequent freeze-thaw cycles or periods with intense precipitation. Signs of rockfall activity are also preserved in the stems of the trees colonizing the Bannwald of Altdorf. According to field data gathered during the «Sanasilva» program, 36% of the trees growing on the slope would show visible signs of past rockfall impacts (Jahn 1988). In addition, debris flows repeatedly occurred in the Kapuzinertal, where they caused loss of human life as well as the destruction of buildings in e.g., 1910 (Niederberger 2002).

As a result of rockfall and debris-flow activity, the Bannwald of Altdorf was first declared «protected» (gebannt) in 1387 AD. Over the centuries, private needs and economic pressures have however led to considerable overuse of the forest, thus hindering permanent forest cover and continuous regeneration, which are preconditions to maintain the protective effect of the stand. In the 19th century, the miserable state of the protection forest made action necessary and, between 1878 and 1885, some 100 000 trees were planted in the Bannwald. Similarly, the construction of protection dams was initiated around 1890. These dams are still in use today, together with protection nets installed along forest roads in the last decades. Today, the forest service of the Korporations-Bürgergemeinde Altdorf extracts approximately 1000 m^3 of wood and invests ca. CHF 220 000 every year to guarantee desirable forest structures and sufficient long-term protection of the village of Altdorf. In late 2002, a guided walk was opened in the Bannwald between Altdorf and Eggberge («schutz.wald. mensch», Lernpfad Altdorf; NIEDERBERGER 2002), illustrating *inter alia* some of the aspects described in this section.

3. Methods

In order to assess the vertical distribution of impacts and to estimate the number of scars still visible on the stem surface, three adult trees with a large number of discernible scars on the stem surface were felled at different locations within the protection forest of Altdorf. In order to respect the influence of microtopography, as well as changes in the slope gradient on bounce heights, two of the trees were sampled in areas with a slope gradient of 45° (*Picea abies, Fagus sylvatica*) and one from a slope gradient of 35° (*Abies alba*). The upslope position of the trees was noted on the stem surface before meter-long pieces were cut between the basal area and the apex of the tree to facilitate transport. Branches were discarded, unless they showed obvious signs of rockfall impacts. In the lab, detailed sketches were established for every single piece of the stem and the vertical position of scars noted. In a further step, the meter-long stem pieces were cut into a large number of cross-sections taken every 10 to 15 cm. For every tree, cross-sections were consecutively numbered, before they were polished and analyzed under the binocular eyepiece. Analysis of the cross-sections mainly focused on the identification of hidden or «internal», overgrown scars and, which were therefore no longer visible on the stem surface (KAENNEL & SCHWEINGRUBER 1995). Subsequently, the age of every single rockfall injury was determined.

4. Results

4.1 Tree data and rockfall scars

A total number of 307 cross-sections were prepared from the three trees. In detail, 105 cross-sections were taken from a 20 m *Abies alba* stem and 114 cross-sections prepared from a 16 m tall *Fagus sylvatica* tree. Finally, 88 stem discs were sawn from the 15 m tall *Picea abies*. Data, including the approximate age of the trees, is given in *table 1*. As the age was assessed at the lowest level of the cross-section, ages given do not, however, represent germination dates.

First and foremost, results indicate that the three selected trees suffered considerable damage from rockfall activity. For instance, the cross-sections analyzed from the 129-year old *Abies alba* stem show signs of the occurrence of 33 rockfall impacts between 1916 and 1996. In the *Fagus sylvatica* tree, 103 scars are identified on the different cross-sections. As several of the rockfall impacts occurred in the same years or might even have been caused by one and the same event, we reduced the number of years with reconstructed rockfall impacts for this tree to 25 between 1898 and 1994. The histogram presented in *figure 1* gives an idea on the temporal distribution of rockfall impacts reconstructed in the *Fagus sylvatica* tree. In addition, it also illustrates one of the lowest cross-sections of the tree with at least a dozen overgrown scars. Finally, the analysis of the *Picea abies* cross-sections enabled us to identify 53 different rockfall impacts, representing more than one recorded event every two years.

4.2 Vertical distribution of scars on stems

Analysis of the vertical distribution of rockfall scars on the stem surface indicate that rockfall can cause damage almost anywhere between ground level and several meters above. As *table 2* illustrates, mean impact heights vary only slightly between the three trees, ranging from 233 cm (*Abies alba*) through 238 cm (*Picea abies*) to 244 cm (*Fagus sylvatica*). In a similar way, minimum impact heights are also comparable with 10, 13 and 17 cm. Scars at this height are most probably the result of rolling rocks impinging on the stem surface. We were unable to identify impact damage lower down on the stem, probably owing to the size of rockfall fragments occurring on the slope. In contrast to the relatively uniform data obtained for the mean and minimum impact heights, maximum impact heights vary considerably. In particular, the extremely

Table 1: **Age, height, number of cross-sections prepared and number of scars reconstructed for the three trees selected from the Bannwald of Altdorf.**

Tree	Tree age	Tree height	Cross-sections	Scars
Abies alba	129 yrs	20 m	105	33
Fagus sylvatica	112 yrs	16 m	114	103
Picea abies	97 yrs	15 m	88	53
Total	–			**189**

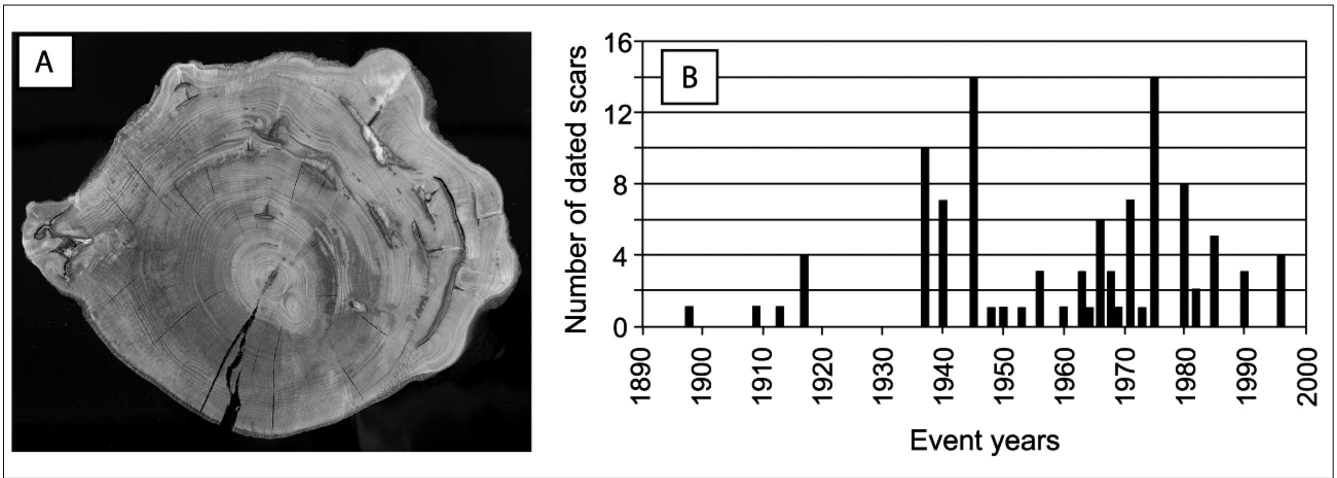

Figure 1: **Rockfall activity based on 114 stem discs of a heavily disturbed beech (*Fagus sylvatica*) from the Bannwald of Altdorf.**

(A) Cross-section taken at the base of the stem showing 13 scars;
(B) Histogram with all event years reconstructed on the stem discs of this beech tree.

high impacts observed in the *Abies alba* stem outstrip expectations by a long way (930 cm). The vertical distribution of impact scars, as well as event years are exemplarily illustrated for the *Abies alba* tree in *figure 2*. The uppermost impact scars observed in the *Fagus sylvatica* and the *Picea abies* stems are, by contrast, located (more than) three meters below and totaled 628 and 596 cm, respectively.

In addition to the minimum, maximum and mean impact heights, the vertical distribution of scars was investigated in greater detail, as shown in *figure 3*. Results obtained for the *Abies alba* tree indicate that more than every second scar is located within the first two meters above ground level (58%). *Figure 3* also shows that more than a quarter of the rockfall wounds identified on the *Abies alba* stem are found within 400 cm, while 10% of all rockfall wounds are identified between 630 and 930 cm above ground. Finally, the diagram indicates that, in contrast to the other two trees, scars are most frequently found between 100 and 199 cm and not within the first meter above ground.

Table 2: Vertical distribution of rockfall scars on trees illustrated with mean, minimum and maximum heights (in cm).

Tree	Mean	Minimum	Maximum
Abies alba	233	17	930
Fagus sylvatica	244	13	628
Picea abies	238	10	596

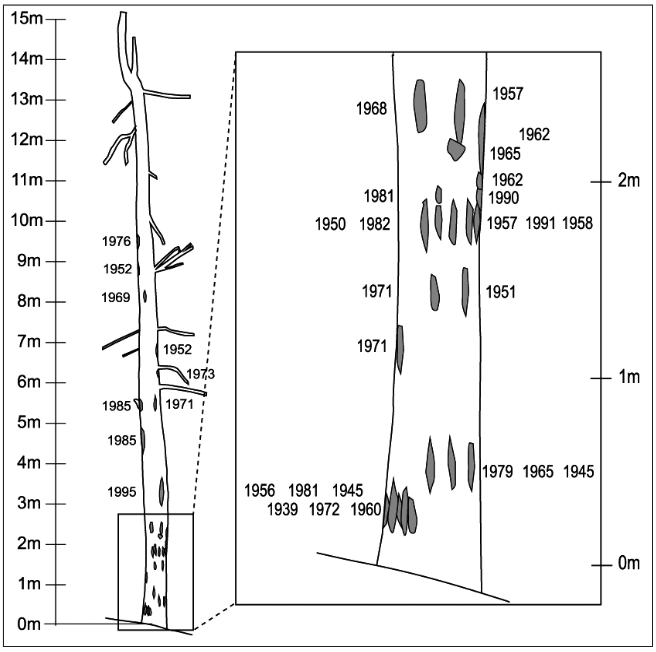

***Figure 2:* Vertical and horizontal distribution of 33 rockfall injuries reconstructed on an adult fir tree (*Abies alba*) from the Bannwald of Altdorf.**

While most scars were recorded within the first 2 m above ground, the highest injury was found at a height of 930 cm.

Data obtained from the *Fagus sylvatica* cross-sections indicates that 50% of all impacts are found below 206 cm, while 75% of the scars occur in the first four meters of the stem (392 cm). *Figure 3* makes clear that this relatively high value is influenced by a large number of rockfall scars identified between 300 and 399 cm above ground. Data further indicate that 90% of all injuries take place below 513 cm and that impacts do not occur over 628 cm.

Analysis of rockfall impacts on the *Picea abies* stem shows a similar distribution to that of the *Fagus sylvatica* tree. Every second scar can be identified within the first 183 cm and 75% of all impacts are located below 381 cm. In a similar way, the 90% level only slightly differs (< 499 cm) from the values obtained for the *Fagus sylvatica* tree (< 513 cm) and, as before, the highest scars identified are found at similar heights. There are, however, differences in the number of scars occurring between 100 and 299 cm, where impacts appear to be more frequent in the *Picea abies* than in the *Fagus sylvatica* tree. Further details on the vertical distribution of the scars can also be found in *figure 3*.

4.3 Visible and hidden scars

From the 189 scars identified in the three trees analyzed from the Bannwald of Altdorf, almost 70% of the wounds would have been identifiable from the outside. By contrast, three out of ten scars would have been missed without cutting the cross-sections. Large differences were ascertained between the different trees, as illustrated in *table 3*. While an aston-

Table 3: Visibility of scars given with the percentage of visible and completely hidden signs of past rockfall activity.

Tree	Visible	Hidden
Abies alba	84%	16%
Fagus sylvatica	75%	25%
Picea abies	51%	49%

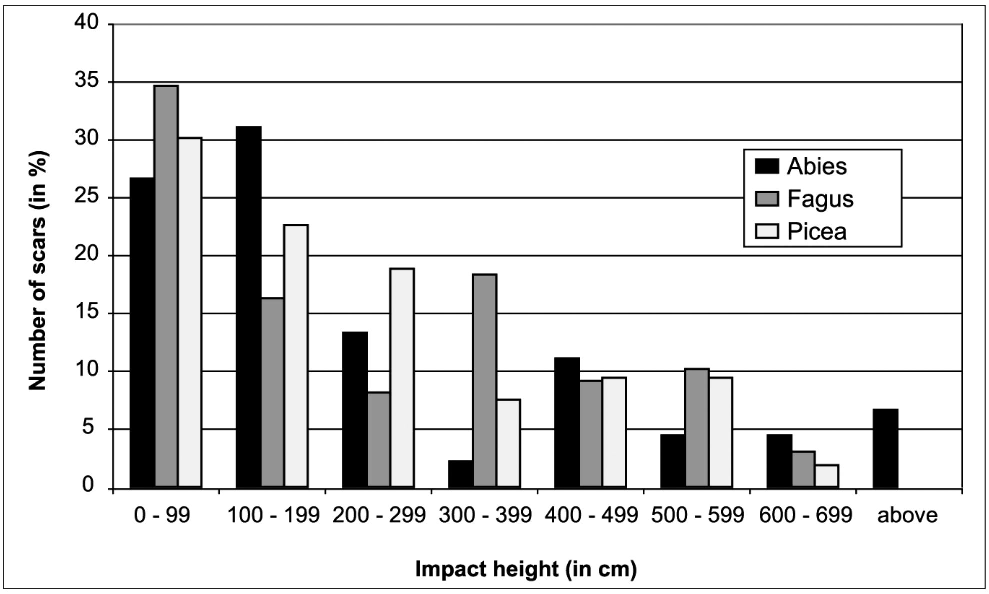

Figure 3:* Vertical distribution of impacts reconstructed in *Abies alba, Fagus sylvatica* and *Picea abies.

ishing 84% of the rockfall scars can still be seen on the stem surface of the 129-year old *Abies alba* tree, only 51% of the rockfall wounds remain visible on the 97-year old *Picea abies* stem. Data from the 112-year old *Fagus sylvatica* tree indicate that three quarters of all scars would have been identified solely by visual analysis.

5. Discussion and conclusion

In the study reported here, we analyzed the vertical distribution of scars of 307 cross-sections prepared from the stems of three trees from the Bannwald of Altdorf and assessed the level of visibility of the scars. Results clearly show that scars could occur from almost ground level to several meters above. In addition, data also indicate that some evidence of past events becomes blurred with time and that only between 51 and 84% of scars actually remain visible on the stem surface.

While the present study provided some further knowledge on the vertical distribution and the visibility of scars on stem surfaces, it also gives rise to numerous questions and research topics for further studies. As only three trees were analyzed, we found considerable differences in the values for the maximum impact heights. Nonetheless, results obtained from the *Abies alba* tree – selected on a surface with a slope gradient of 35° – suggest that RICKLI *et al.* (2004) underestimate maximum bounce heights of rocks (Ø < 50 cm) and boulders (Ø > 50 cm) on forested slopes with a gradient of 35°, probably even by several meters! By contrast, data gathered from *Fagus sylvatica* and *Picea abies* trees cannot be compared with the results of RICKLI *et al.* (2004), as these trees were selected on terrains with steeper slope gradients (45°).

Results further suggest that, on average, «only» 54% of the scars are to be found within the first two meters above ground, whereas 11% of the scars are located at least five meters above the ground. Why do we have such high bounces in the present case? Are they the result of the comparably steep slope gradients, microtopography or the size of the rockfall fragments present at the Bannwald of Altdorf? And do comparable impact heights occur on other sites as well? If so, how do we need to take these impact heights into account when dimensioning rockfall barriers or restraining nets?

As for the visibility of scars on the stem surface, results more or less coincide with data obtained at Brienzergrat (Berne, Switzerland), where GSTEIGER (1989, 1993) assessed hidden scars in seven *Fagus sylvatica* and *Picea abies* trees. In contrast, data is contradictory on results obtained in a century-old *Larix decidua* Mill. stand near Täsch (Valais, Switzerland), where only 8 to 10% of the scars remained visible on the stem surface (SCHNEUWLY 2003, STOFFEL *et al.* 2005a, 2005b). As a consequence, the considerable differences occurring in the number of scars remaining visible on the stem surface should be addressed in greater detail. At first view, bark properties seem to influence the visibility of scars. Data suggests that the sporadic removal of bark pieces («peeling») occurring in some of the conifer species, such as, e.g., *Picea abies* or *Larix decidua*, apparently helps to blur much more evidence from past events than does the smooth and thin bark of, e.g., *Fagus sylvatica*. Is there a relation between bark properties and the visibility of past impacts? Does the predominant size of rockfall fragments influence the size of scars and, as a consequence, the time they remain visible on the stem surface? Is it rather the vitality and yearly increment that drive the overgrowing process of scars and the blurring of past impacts? Or is it perhaps a combination of several of these factors?

In addition, current dendrogeomorphological methods in rockfall research should be critically examined: What percentage of rockfall events are we able to reconstruct at sampling height, faced with the proof that impacts can occur almost anywhere between ground level and several meters above? Might studies using increment cores furnish reliable results and how much data on the total number of scars could they provide? There is, indeed, considerable necessity for further research. In particular, replicate studies are needed from a variety of sites in order to assess maximum impact heights occurring on forested rockfall slopes, and to identify the importance of hidden scars.

Summary

Rockfall generally consists of individual rocks and boulders moving down slope in a falling, bouncing or rolling motion. As a result, impacts on trees can occur almost anywhere between ground level and several meters above. The present paper therefore focuses on the vertical distribution and the visibility of scars on stem surfaces. Three adult trees from the Bannwald of Altdorf were sawn into 307 cross-sections in order to determine impact heights and to assess the number of hidden scars no longer visible from outside. Results indicate that scars can be observed at heights of up to nine meters or more. Depending on the tree species selected, «blurred evidence» accounted for 16 to 49%. We can suppose that bark properties might influence the blurring of scars.

Zusammenfassung

Untersuchung der vertikalen Verteilung und der Sichtbarkeit von Steinschlagverletzungen an und in Bäumen

Unter Steinschlag versteht man gemeinhin die fallende, springende oder rollende Abwärtsbewegung von Einzelsteinen und -blöcken. Tritt Steinschlag in bewaldeten Hängen auf, so können Baumtreffer aufgrund der unterschiedlichen Bewegungsmechanismen sowohl in Bodennähe wie auch in mehreren Metern Höhe festgestellt werden. Der vorliegende Aufsatz zielt deshalb auf die vertikale Verteilung der Schäden sowie die Sichtbarkeit von Verletzungen auf Stammoberflächen ab. Untersuchungen an 307 Stammscheiben von drei adulten Bäumen aus dem Bannwald von Altdorf zeigen, dass Steinschlagschäden bis in Höhen von mehr als neun Metern auftreten können. Daneben fällt auch auf, dass ein Teil der Schäden von aussen nicht mehr sichtbar ist. Je nach Baumart variiert der Anteil der «versteckten» Schäden zwischen 16 und 49%. Es wird davon ausgegangen, dass unterschiedliche Borkeneigenschaften die Überwallung unterschiedlich stark beeinflussen.

Résumé

Analyse de la répartition verticale et de la visibilité des cicatrices causées sur les arbres par des chutes de pierres

Les chutes de pierres se manifestent sous forme de chute libre, saut ou roulement de pierres ou blocs individuels. En forêt, ces différents phénomènes peuvent causer des impacts sur les arbres, tant à proximité du sol qu'à plusieurs mètres en dessus. La présente publication a pour but d'analyser la répartition verticale des cicatrices sur le tronc des arbres ainsi que leur visibilité. Pour ce faire, 307 disques provenant de trois arbres adultes du Bannwald d'Altdorf ont été prélevés afin de démontrer que les cicatrices causées par les chutes de pierres peuvent se trouver à des hauteurs allant jusqu'à 9 mètres. En outre, l'étude montre que certaines blessures ne sont plus visibles sur l'écorce même de l'arbre. Selon l'espèce choisie, ce nomb-

re de cicatrices «cachées» varie entre 16 et 49%, raison pour laquelle on part du principe que les différentes propriétés des écorces (épaisseur, écaillement) influencent le processus de cicatrisation de manière variée.

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