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Coarse woody debris in a Carpathian subalpine spruce forest

Totholz in einem subalpinen Fichtenwald der Karpaten

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Summary

Number, volume and size of snags, broken and uprooted trees as well as advancement of their decomposition and arrangement were analysed in a subalpine spruce forest in the Babia Góra massif (West Carpathians). The most important results are:

1. The amount of coarse woody debris noted on Babia Góra was among the highest in subalpine spruce forests, however it was lower than in unmanaged boreal spruce forests, and much lower than in the mountain and boreal forests of North America.
2. Most trees died standing, whereas uprooting was the rarest cause of mortality. The probability that a tree would die standing was greatest among thinnest and thickest individuals. The greater the diameter of spruce the higher was the probability of breakage. Uprooting was most common among trees of moderate diameter.
3. Snags and broken stems were randomly distributed, whereas windthrows were clumped.
4. Decomposition of spruce logs was a very slow process as these logs remain visible on the soil surface for about 150 years after tree death. The process is slower than in central Sweden, but much quicker than in boreal forests of northern Sweden.
5. The diameter of dead trees and the spatial pattern of stand breakdown changed in recent years as a result of stand development and changes of causal factors.
6. In recent years intensity of stand breakdown was nearly two times higher than stand growth when the volume of the trees was taken into account. This indicates the probability of the stand to enter the breakdown stadium.

Keywords: subalpine spruce forest, coarse woody debris, W Carpathians, S Poland.

Zusammenfassung

In einem subalpinen Fichtenwald des Babia Góra-Massivs (West-Karpaten) wurden Anzahl, Volumen und Größe von stehenden, gebrochenen und entwurzelten Totholzstämmen nebst ihrem Zersetzungsgrad und ihrer räumlichen Anordnung analysiert. Die wichtigsten Ergebnisse waren:

1. Die am Babia Góra gefundene Totholzmenge gehört zu den höchsten, die bislang in subalpinen Fichtenwäldern des temperierten Europa festgestellt wurde, jedoch war sie geringer als in unbewirtschafteten borealen Fichtenwäldern und viel geringer als in Nadelwäldern der Gebirge und der borealen Zone Nordamerikas.
2. Die meisten Bäume waren stehend abgestorben, während Windwurf die seltenste Mortalitätsursache war. Die Wahrscheinlichkeit des Absterbens war am höchsten unter den Individuen der geringsten und der stärksten Durchmesserklassen. Die Wahrscheinlichkeit von Stammbrüchen nahm mit steigendem Durchmesser zu. Windwurf war unter den Bäumen mittleren Durchmessers am häufigsten.
3. Stehendes und gebrochenes Totholz war zufällig verteilt, während Windwürfe räumlich aggregiert auftraten.
4. Die Zersetzung von Fichtenstämmen vollzieht sich sehr langsam, wie noch nach ca. 150 Jahren nach Absterben erkennbare Reste belegen. Der Prozess verläuft langsamer als in Zentralschweden, jedoch viel schneller als in borealen Wäldern Nordschwedens.
5. Die Durchmesserverteilung des Totholzes und das räumliche Muster der Bestandeszusammenbrüche unterlag in den letzten 20 Jahren Veränderungen, die durch die Bestandesentwicklung und eine geänderte Häufigkeit der einzelnen Mortalitätsurachen bedingt war.
6. In den letzten Jahren war das Volumen absterbender Bäume nahezu doppelt so hoch wie der Zuwachs der verbleibenden Bestandesglieder.

Schlüsselwörter: subalpiner Fichtenwald, Totholz, West-Karpaten, Süd-Polen.

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1 Introduction

Dead trees are important structural elements of forest ecosystems, and the role they play in many processes is well documented. Logs play a role in protecting saplings by constraining movement of ungulate herbivores and they also are a substrate used in regeneration of trees (AGEE & SMITH 1984, WEBB 1988, STEWART 1989, PETERSON & PICKETT 1995). Coarse woody debris (CWD) has been shown to be particularly important in the process of Norway spruce (*Picea abies* (L.) Karst.) regeneration (MAYER et al. 1972, HYTTEBORN & PACKHAM 1987, HOFGAARD 1993 [a], REIF & PRZYBILLA 1995, HÖRNBERG et al. 1997).

Dead trees support the existence of thousands of species of insects, mites, mosses, liverworts, algae, lichens, fungi and bacteria, and must be regarded as one of the major sources of forest biodiversity (MASER & TRAPPE 1984, BAŁAZY & WIŚNIEWSKI 1987, VAISANEN at al. 1993). Presence of dying and dead trees is favorable for birds, especially for cave nesters (WESOŁOWSKI & TOMIAŁOJĆ 1986). Logs lying across slopes stop litter and small stones moving down the slope. Prevention of snow movement on steep slopes protects young trees against bending, breaking and uprooting (AGEE & SMITH 1984).

Quantitative and qualitative characteristics of CWD were conducted for many forest types. The most abundant data are from boreal and temperate forests of North America. In Europe detailed studies on dead trees were first carried out in Scandinavia. The wealth of data from North America and Scandinavia is related to high degree of pristine forests found in these regions. Only few such studies were carried out in Central and Western Europe. One data set comes from the Polish Białowieża Forest (FALIŃSKI 1978). There are no detailed studies on CWD in the Carpathian forests in spite of their natural character over large areas. Data collected until now are limited to the volume and widely defined stages of decomposition and come from small areas (SANIGA & SKLENAR 1989, KORPEL' 1989 and 1993, JAWORSKI & KARCZMARSKI 1995).

This paper gives detailed and representative characteristics of CWD quantities and an analysis of its temporal and spatial distribution in a subalpine spruce forest, which has been protected and from which no timber extraction has occured for almost 70 years. The investigations also include causes of tree mortality and rate of CWD decay. Using a large plot (nearly 15 ha) allowed analysis of the spatial pattern in a scale several times larger than the area of homogenous stands. The findings will be compared to results from other unmanaged spruce forests in the Carpathians, the Alps, and Scandinavia.

The article is a part of a larger project on the structure and dynamics of the Carpathian subalpine spruce forest. The material has already been published in Polish (HOLEKSA 1998).

2 Site description

The investigation was carried out in the Babia Góra massif (1725 m), the highest area in the West Beskids. The soils are mainly humus-iron podzols, iron podzols and podzolised rankers. They developed from magurian sandstone with mudstone intercalations (ADAMCZYK 1989). At the altitude of subalpine spruce forests (1150–1400 m) the climate is cool with a mean annual temperature of 2–4 °C, mean annual rainfall of 1470 mm, snow depth of 1–2 m, and a snow free period of about 7 months (OBRĘBSKA-STARKLOWA 1983, HOLEKSA & PARUSEL 1989). Strong descending winds occur regularly at speeds of more than 15 m/sec.

The investigated spruce forest has been under protection since 1930. In 1955 it was included into a strict reserve of the Babia Góra National Park which is now a biosphere reserve.

The 14.4 ha (340 × 424 m) plot was placed at an elevation 1188–1300 m. According to MYCZKOWSKI (1964) and KORPEL' (1980) only the lower portion of the subalpine spruce belt with dense stands is represented in the plot, and loose stands below the upper forest

Table 1. Characteristics of the investigated tree stand (HOLEKSA 1998).
Tabelle 1. Kennwerte der Untersuchungsbestände (HOLEKSA 1998).

Species	Number of trees (n/ha)	Basal area (m^2/ha)	Volume (m^3/ha)
Picea abies[1]	258 ± 15[3]	36.3 ± 2.3[3]	407 ± 26[3]
Sorbus aucuparia[2]	4	0.05	–
Fagus sylvatica[2]	< 1	< 0.01	–

[1] Trees of dbh ≥ 10 cm were measured on 100 circular plots of 0.01 ha;
[2] All trees ≥ 10 cm over the whole 14.4 ha investigation area were measured; [3] Mean ± standard error

limit were excluded. Small patches within the plot are covered by tall-herb communities (Betulo-Adenostyletea), vegetation of springs (Montio-Cardaminetea), and an association of microtrophic mires (Caricetum fuscae). The landforms of the investigated area include a wide plateau, a large area of gentle slopes 5–15°, and small fragments of steep slopes inclined up to 40°. Slopes are mostly exposed to the north and northeast.

Basic characteristics of the investigated spruce stand are given in table 1.

3 Methods

Measurements of dead trees. All snags, logs, and their fragments with diameter at breast height or with maximum diameter ≥ 10 cm, and height (length) ≥ 3 m were mapped over the whole 14.4 ha area. Logs were divided into broken and uprooted. Dbh and height of snags, length and diameter at both ends of logs, and dbh of logs (if its position could be determined) were measured. Diameters of stump tops were estimated roughly. The volume of intact snags and logs was calculated using the volume tables of GRUNDNER & SCHWAPPACH (1952). The volume of stumps and log fragments was calculated using the equation for the volume of truncated cone.

For each log the total area of its projection on the slope surface and the length and projection area of 10-cm diameter sections were calculated. These diameter sections were: 10-20, 20.1–30, ... 60.1–70, > 70 cm. The following equations were used:

$$P = 1/2\,(D + d)\,L$$
$$l_{a+b} = L\,(a - b)/(D - d)$$
$$P_{a+b} = l_{a+b}\,(a + b)/2$$

L and P are the total length of log and total area of log projection; D and d are the maximum and minimum diameters of a log; l_{a+b} and P_{a+b} are the length and the projection area of a log section with diameters a and b on its ends.

Each snag and log was classified according to the advancement of its decomposition using an eight-degree scale (Tab. 2). The first class of decomposition is further divided with regard to the amount of twigs, branches and boughs into three subclasses (DYNESIUS & JONNSON 1991). Every log was classified according to the predominant class of its decomposition.

Whenever differences in dbh between CWD and living trees or between different groups of CWD were analysed for significance, the nonparametric KOLMOGOROV-SMIRNOV test was used as dbh distribution differed significantly from normal.

Rate of decomposition. To asses the time elapsed from tree death to an observed class of decomposition two dendrochronological methods were used (DYNESIUS & JONNSON 1991). The first method uses the growth release of a neighboring tree recorded in its increment rings. It gives an exact date of tree death. 84 trees were cored at 1.3 m on the side facing a

Table 2. Characteristics of snags and logs in different classes of decomposition.
Tabelle 2. Kennwerte von stehendem und liegendem Totholz in verschiedenen Zersetzungsklassen.

Class of decomposition	Surface	Shape	Depth of penetration by sharp object	Location (only logs concerned)	Branches	Bark
I.1	smooth	round	wood is solid	supported by branches and highly elevated above ground	youngest 1–2 years old twigs are present	most often covers the whole log (partial lack of bark caused by bark beetles and woodpeckers)
I.2					without 1–2 years old twigs, branches up to 5 mm thick are present	
I.3					without branches up to 5 mm thick, only thicker branches and poorly branched boughs and stubs	
II	smooth	round	surface only bends under the pressure of a sharp object	supported by thick boughs and elevated above ground	only thick boughs and their stubs present	tears off from bottom surface; lacks on snags
III	crevices several mm deep are present	round	to 1 cm	supported by bough stubs and slightly elevated above ground	only stubs of at least 2 cm thick present	occasionally present on upper surface
IV	crevices about 0,5 cm deep are present	round	to 3 cm	partly in contact with ground	only stubs at least 4–5 cm thick present	usually lack of any remnants
V	thick (several cm) pieces of wood tear off from the bottom surface; sides are cracked with crevices 1 cm deep	round	to 5 cm	in contact with ground along the whole length; elevated only over small depressions	lack of any remnants	lack of any remnants
VI	thick (several cm) pieces of wood tear off from sides	round	solid pieces of wood only in the central part of log	entirely adheres to the ground	lack of any remnants	lack of any remnants
VII	the whole log is covered with crevices several cm deep	distinctly flattened	through	entirely adheres to ground	lack of any remnants	lack of any remnants
VIII	most often totally covered with mosses and vascular plants	creates long structure elevated above the ground	through	joined with ground	lack of any remnants	lack of any remnants

dead neighbor. The year of release was determined from an analysis of the ring sequence. Only 39 samples with one distinct growth release or with large distances between consecutive releases were accepted.

The second method uses the age of trees growing on logs. It allows assessment of only the minimum time span since tree death. The 8 thickest spruces growing on logs in classes V–VIII of decomposition were cored at the stem base.

Spatial pattern of dead trees. Spatial pattern of dead trees was analysed with the RIPLEY's method (DIGGLE 1983). According to this method around each object all neighbours are counted within a circle of radius t. Value of t increases gradually up to its maximum T. For each t value a function $L(t)$ is calculated and significance of departure from random distribution is tested. This method allows analysis of spatial distribution of point objects (dead trees in this case) simultaneously in different spatial scale. It was possible to use this method as the location of every snag and log was marked on a detailed map scaled 1:500. The analyses were performed with a computer program called PATARUNO (PTAK, unpublished material). As this program is designed for circular plots, it was necessary to limit the analysis of CWD distribution to the circle of r = 170 m (9.08 ha) situated at the plot center. Stable 95% confidence intervals were accepted in testing significance of departure from a random distribution (SZWAGRZYK & PTAK 1991). The analysis was performed for a radius around every object (t) ranging from 1 to 50 m.

Relative intensity of stand breakdown. The volume of dead trees representing subclass I.1 of decomposition was compared to the volume increment of the whole stand in the years 1987–1993. It was stated that most dead trees in I.1 subclass died during this time (see Fig. 6).

Stand volume was calculated on the basis of dbh and height measurements of trees ≥ 10 cm dbh on 100 circular 0.01 ha plots forming a 40 × 40 m network over the whole 14.4 ha area. The volume of each tree was then read in GRUNDNER & SCHWAPPACH (1952) tables.

Volume growth of stand in the years 1987–1993 was calculated as the sum of increment of trees that were alive in 1993 and trees that died in this period, i. e. trees that in 1993 represented the subclass I.1 of decomposition. To calculate the volume increment of trees living in 1993, at each of 100 points the nearest tree was cored at 1.3 m and the total width of the seven recent rings was measured. There was no significant relationship between seven-year dbh increment and dbh in 1993. Thus, to calculate dbh of trees in 1987 the average seven-year increment ($\Delta dbh_{1987-1993}$) was extracted from dbh of all trees on 0.01 ha plots. The volume of trees in 1987 was then calculated on the basis of the relationship between tree dbh and tree volume obtained for all trees on 100 circular 0.01 ha plots from GRUNDNER & SCHWAPPACH (1952) tables.

It was assumed that the volume of snags and logs in the subclass I.1 of decomposition in 1993 was equal to the volume of trees just before they died (dbh_{death}) and that the death rate of trees in 1987–1993 was constant. If the second assumption is true, for every snag and log:

$$dbh_{1987} = dbh_{death} - \tfrac{1}{2}\Delta dbh_{1987-1993}.$$

For this group of trees the volume in 1987 and in the year of death was then calculated using the relationship between tree dbh and tree volume.

4 Results

Quantitative characteristics of coarse woody debris. On average there were 194 dead trees and 131 m^3 of dead wood per 1 ha (Tab. 3). This corresponds to 43% of the total number and 24% of the total volume of living and dead trees. The first value is probably an

Table 3. Number and volume of snags and logs in different classes of decomposition.
Tabelle 3. Zahl und Volumen von stehenden und liegenden Totholzstämmen in den Zersetzungsklassen.

Class of decomposition	Snags		Logs	
	n/ha	m^3/ha	n/ha	m^3/ha
I.1	23.2	27.1	9.5	9.2
I.2	26.6	22.7	5.1	4.1
I.3	28.1	8.0	8.7	5.4
II	4.2	0.7	12.7	6.6
III	–	–	12.9	8.3
IV	–	–	25.3	15.4
V	–	–	12.9	8.0
VI	–	–	13.1	9.1
VII	–	–	7.7	3.7
VIII	–	–	4.8	2.8
Total	82.1	58.5	112.3	72.6

overestimation as in some cases separate pieces of wood may have been fragments of the same log.

Most dead standing trees and logs represented class I of decomposition (Tab. 3). Dead trees in subclasses I.1, I.2 and I.3 were similar in number, but the least decomposed (subclass I.1) were of the largest volume. Another peak in CWD quantity was in class IV of decomposition.

The ratio of the number of CWD in subclass I.1 of decomposition to the sum of trees still alive in 1993 and CWD in subclass I.1 indicates the intensity of recent tree mortality. Every forth tree died from among the thinnest (dbh 10–20 cm), however in the next dbh classes fewer trees died (Fig. 1). This diminishing trend was reversed for dbh > 40 cm, while for the thickest trees 12% died. The difference in dbh structure between dead trees in subclass I.1 and trees living several years ago (subclass I.1 + living trees) is significant (KOLMOGOROV-SMIRNOV test: $D = 0{,}290$, $n_1 = 293$, $n_2 = 450$, $p < 0{,}001$). It indicates that mor-

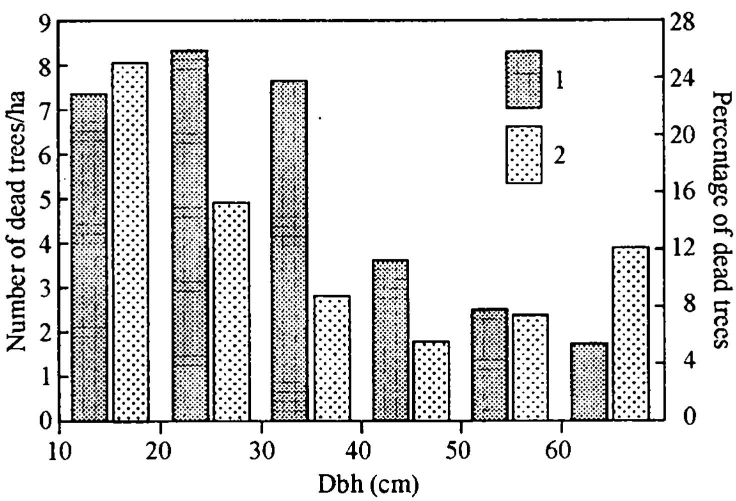

Fig. 1. Dead trees in class I.1 of decomposition: diameter distribution (1) and percentage of dead trees in relation to the sum of living trees and dead trees in class I.1 (2).

Abb. 1. Tote Bäume der Zersetzungsklasse I.1: Durchmesserverteilung (1) und Anteil toter Bäume bezogen auf die Zahl der lebenden Bäume und die toten Stämme der Klasse I.1 (2).

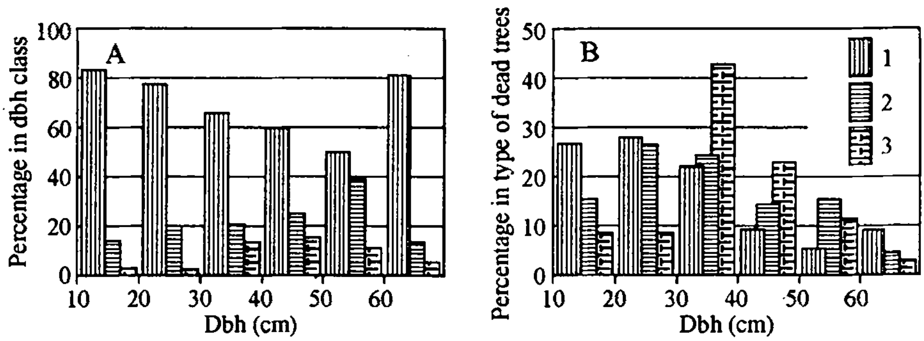

Fig. 2. Percentage of different types of dead trees in diameter classes (A: 100% = all trees in a diameter class) and diameter distribution in different types of dead trees (B: 100% = all trees of a particular type); types of dead trees: 1: snags, 2: broken, 3: uprooted.

Abb. 2. Anteil verschiedener Typen toter Bäume nach Durchmesserklasse (A: 100 % = alle Bäume einer Durchmesserklasse) und Durchmesserverteilung innerhalb der Totholztypen (B: 100 % = alle Bäume des Typs); Totholztypen: 1: stehend, 2: abgebrochen, 3: liegend.

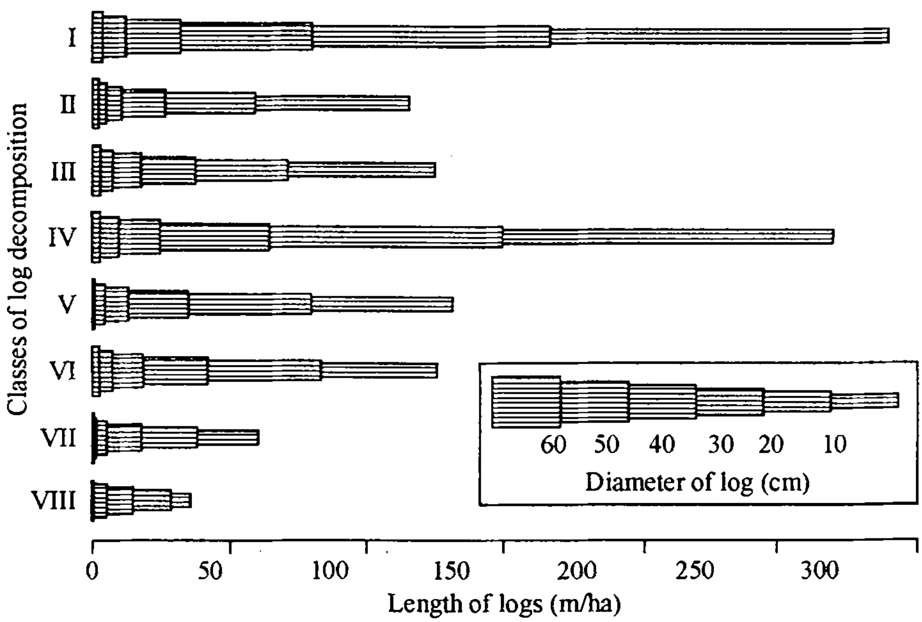

Fig. 3. Length of logs according to classes of decomposition (each log represents only one prevailing class of decomposition) and according to diameter classes (each log is divided into sections representing different diameter classes).

Abb. 3. Stammlängen nach Zersetzungsklassen (jeder Stamm wurde einer vorherrschenden Zersetzungsklasse zugeordnet) und nach Durchmesserklassen (jeder Stamm wurde in Abschnitte unterschiedlicher Durchmesserklasse gegliedert).

tality probability of a tree depends on its size – it is higher for the thinnest and the thickest trees than for trees of intermediate size.

Dead standing trees made up 42% and 45% of the whole dead stem number and volume, respectively. The cause of mortality (dead standing, broken, uprooted) can be determined only on the basis of dead trees in subclass I.1 of decomposition. Later, the standing trees break down and it was difficult to distinguish between dead standing and broken. Snags make nearly ¾ of all recently dead trees, about 20% were broken; only 7% of the trees were uprooted.

Snags are most numeros in all dbh classes within subclass I.1 of decomposition. The greatest probability that a tree died standing was in the smallest and the largest classes (Fig. 2A). The percentage of broken trees increases gradually up to the dbh class 50–60 cm. Uprooting was very rare among the thinnest as well as among the thickest trees; their percentage peaked in class 40–50 cm. The dbh structure of every category of dead trees was different (Fig. 2B) (KOLMOGOROV-SMIRNOV test, snags–broken: $D = 0.180$, $n_1 = 334$, $n_2 = 91$, $p = 0.02$; snags–uprooted: $D = 0.399$, $n_1 = 334$, $n_2 = 35$, $p < 0.001$; broken–uprooted: $D = 0.275$, $n_1 = 91$, $n_2 = 35$, $p = 0.048$).

The total length and area of logs was 1187 m/ha and 300 m²/ha. Most logs represented classes I and IV of decomposition (Figs 3, 4A). The thinnest logs (diameter 10–20 cm) dominated in respect to length (490 m/ha), however in regards area the next diameter class (21–30 cm) dominated with 92 m²/ha. The length and area of very thick logs (diameter > 50 cm) were 49 m/ha and 30 m²/ha (Figs. 3, 4B).

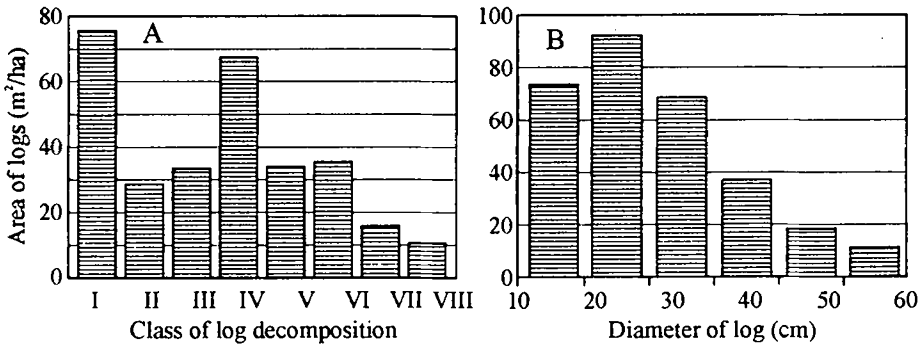

Fig. 4. Area of logs according to classes of decomposition (A) (each log represents only one prevailing class of decomposition) and according to diameter classes (B) (each log is divided into sections representing different diameter classes).

Abb. 4. Horizontalfläche von Stämmen nach ihrem Zersetzungsgrad (A) (jeder Stamm wurde einer vorherrschenden Zersetzungsklasse zugeordnet) und nach Durchmesserklassen (jeder Stamm wurde in Abschnitte unterschiedlicher Durchmesserklasse gegliedert).

Spatial pattern of coarse woody debris. The spatial patterns of snags, broken trees and uprooted trees were analysed for subclass I.1 of decomposition only. In addition, the spatial pattern of uprooted trees was analysed for all stages of decomposition as they could be recognised regardless of the stage of decomposition.

The distribution of snags and broken trees did not differ from random in the whole range of analysed spatial scales, whereas uprooted trees occurred in clumps (Fig. 5). For uprooted trees in the subclass I.1 of decomposition the significant departure from random distribution was found for the t value between 9 and 21 m, and above 34 m. For all uprooted trees the clumped distribution was observed from 1 to 50 m (Fig. 5).

Dead trees in class II of decomposition showed a tendency to clump at $t < 30$ m. Logs in classes I.3 and IV formed clumps in the whole range of analysed t, and logs in classes V and VI at $t > 20$ m. Recently dead trees in subclasses I.1 and I.2 were distributed randomly. Also distribution of logs in classes VII and VIII did not differ significantly from random, but they were very small in number.

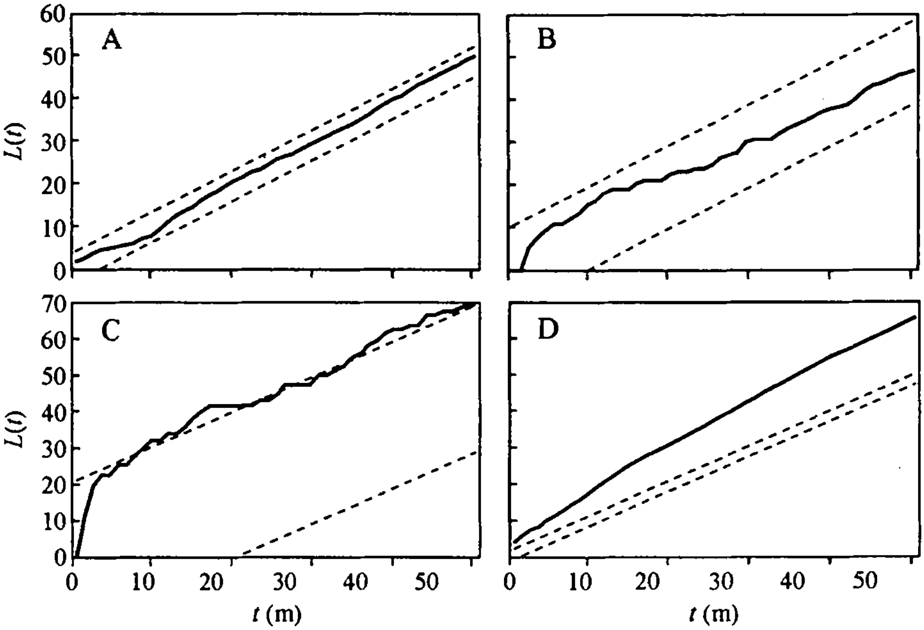

Fig. 5. Results of the analyses of spatial pattern of snags (A), broken trees (B) and uprooted trees in class I.1 of decomposition (C), and uprooted trees in all classes of decomposition (D); solid lines are graphs of function *L(t)* for different types of dead trees, dashed lines delimit the area of random distribution, the area of clumped distribution is above.

Abb. 5. Analyse der räumlichen Muster von stehendem Totholz (A), abgebrochenen Bäumen (B) und liegendem Totholz der Zersetzungsklasse I.1 (C) sowie von liegendem Totholz aller Zersetzungsklassen (D); durchgezogene Linien stellen die Funktion *L(t)* für verschiedene Totholzarten dar, gestrichelte Linien begrenzen die Fläche einer Zufallsverteilung, oberhalb derer geklumpte Verteilungen vorliegen.

Rate of decomposition of CWD. Most dead trees representing class I of decomposition died less than 10 years ago (Fig. 6). CWD in class II originated 10–18 years ago. Logs in class III was dated between 20–36 years. Logs in classes IV and V were remnants of trees that died 32–57 years ago. For logs in class VI 45–78 years was obtained when growth release of suppressed trees was taken into account, and at least 44–59 when the age of young trees growing on logs was used. Logs in class VII had decayed for 68–107 years (growth release method), or at least 73 years (young tree method). The age of three spruces growing on logs representing the class VIII were 80, 120 and 128 years.

Temporary changes in tree mortality. The intensity of tree death in the years 1987–1993 was established on the basis of CWD in subclass I.1 of decomposition. The intensity was 4.6 trees $\cdot$ $ha^{-1} \cdot year^{-1}$ and 5.2 $m^3 \cdot ha^{-1} \cdot year^{-1}$. It was 1.8% of the number of living trees and 1.3% of the stand volume in 1993 (compare Tab. 1).

There were 1224 snags and logs representing classes I.2, I.3 and II of decomposition over an area of 14.4 ha. Their total volume was 684 m^3. It can be accepted that this amount of CWD originated primarily during 13 years (1974–1986, compare Fig. 6). The established intensity of tree death in years 1974–1986 was 6.5 trees $\cdot$ $ha^{-1} \cdot year^{-1}$ and 3.7 $m^3 \cdot ha^{-1} \cdot year^{-1}$.

The values for 1974–1986 and 1987–1993 make it clear that thicker trees were dying after 1986 – despite their smaller number total volume was higher. The amounts of CWD in consecutive classes of decomposition indicate that intensity of tree death increased during the last 20 years. Dead trunks remain in class I for less than 20 years, whereas logs bear

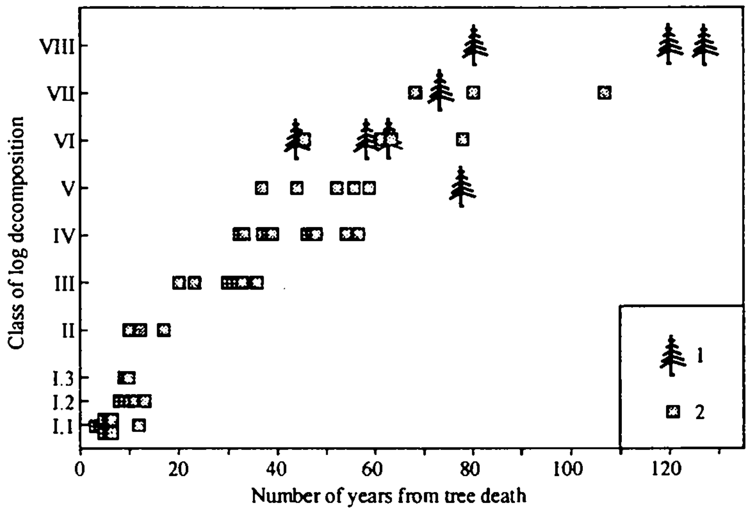

Fig. 6. Time elapsed between spruce death and accession to different classes of decomposition; two methods of dating were used: age of young tree on fallen log (1) or the growth release of suppressed neighbour (2).

Abb. 6. Zeit zwischen dem Tod von Fichten und dem Erreichen von Zersetzungsklassen; zwei Datierungsmethoden kamen zum Einsatz: Altersbestimmung an Jungwuchs auf liegendem Totholz (1) oder Registrierung der Wachstumsreaktion an Nachbarbäumen (2).

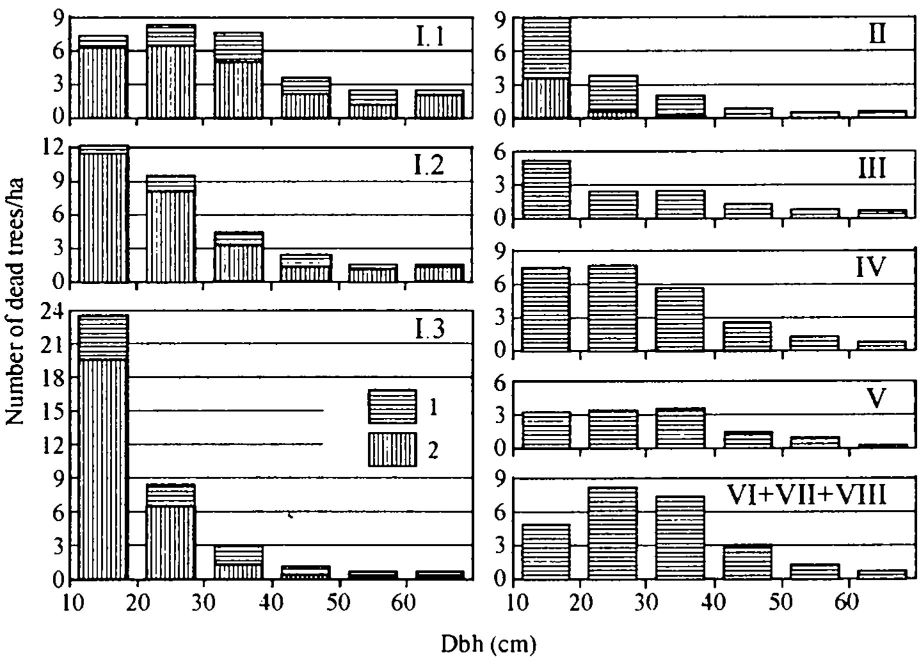

Fig. 7. Diameter distribution of dead trees in different classes of decomposition with regard to logs (1) and snags (2).

Abb. 7. Durchmesserverteilung toter Bäume unterschiedlichen Zersetzungsgrades gegliedert nach liegendem (1) und stehendem (2) Totholz.

features typical for classes III, IV or V much longer (Fig. 6). In spite of this, the number and volume of snags and logs in class I were much higher than in the next classes (Tab. 3). The percentage of small snags and logs (dbh ≤ 20 cm) reached its maximum for subclass I.3 of decomposition (Fig. 7). It indicates the very high mortality of thin trees 10–20 years ago. Since that time thick trees have been eliminated with increasing intensity. It is shown by the increasing percentage of dead trees more than 30 cm thick from subclasses I.3 through I.2 to I.1 (Fig. 7).

Increment of volume of tree stand in 1987–1993. Dbh in 1993 was measured to the nearest cm, and the average increment of dbh was 0.9 cm per seven years. To get this average increment in 1987–1993, dbh_{1987} and dbh_{1993} were equal for 10% randomly chosen trees, and they differed by 1 cm for the rest 90% trees.

The calculated increment for the seven years period was 20.4 m^3 per ha, or 2.9 $m^3 \cdot ha^{-1} \cdot year^{-1}$. This figure is nearly two times lower than the intensity of tree death obtained on the basis of CWD in I.1 subclass of decomposition.

5 Discussion

The average amount of coarse woody debris found in this study is similar to values recorded in other parts of Babia Góra (KORPEL' 1989, JAWORSKI & KARCZMARSKI 1989, 1995) and in the Tatra Mountains (KORPEL' 1993). However it is much higher than in Pilsko massif (also in the West Beskids; SANIGA & SKLENAR 1989) and in the Wettersteinwald Reserve (the Alps; RAUH & SCHMITT 1991) (Tab. 4). It should be noted that all values for Carpathian forests were obtained on a limited number (3–5) of small areas of 0.5 ha. The very low value from Pilsko reserve is probably due to extraction of timber in the past. The amount of CWD in Wettersteinwald Reserve is also lower than in the Tatras and Babia Góra. However there is no information about when the extraction of wood was stopped in this Alpine reserve (RAUH & SCHMITT 1991).

On the other hand, the volume of dead trees in the Carpathian subalpine spruce forest is lower than in an unmanaged boreal spruce forest, where 200 m^3/ha was noted (HOFGAARD 1993 [a]). It is also much less than in most natural coniferous forests of North America. In the mountain and boreal forests of USA and Canada the volume of CWD was in the range of 30–1400 m^3/ha (FAHEY 1983, HARMON et al. 1986, 1987, ARTHUR & FAHEY 1990). Also the area covered with logs on Babia Góra is one of the lowest. For example, 300 m^2 of logs

Table 4. Volume of coarse woody debris in subalpine spruce forest in different mountain massifs.
Tabelle 4. Totholz-Volumenvorräte in subalpinen Fichtenwäldern verschiedener Gebirgsmassive.

Locality	Year	m^3/ha	Source
Northern slope of Babia Góra	1995	131	This study
Southern slope of Pilsko (Beskids)	1977 1987	50 55	SANIGA & SKLENAR (1989)
Southern slope of Babia Góra	1980 1987	158 161	KORPEL' (1989)
Northern slope of Babia Góra	1984 1994	92 165	JAWORSKI & KARCZMARSKI (1989) JAWORSKI & KARCZMARSKI (1995)
Kotlový Žľab Reserve (Tatra Mts.)	1968 1978 1988	109 131 159	KORPEL' (1993)
Wettersteinwald Reserve (Alps)	1985	84	RAUH & SCHMITT (1991)

per 1 ha noted in this study is three to seven times lower than in subalpine forests with *Picea engelmannii* and *Abies lasiocarpa* (ARTHUR & FAHEY 1990, ROOVERS & REBERTUS 1993).

As a shallow rooted species, spruce is very sensitive to uprooting (SCHMIDT-VOGt et al. 1987). Nevertheless uprooted trees are very rare in the Babia Góra forest and they make up only 7% of all dead trees. This is three times less than in a subalpine spruce forest in Ukrainian Carpathians (ULANOVA 1991) and 3–8 times less than in boreal spruce forest of Sweden (HYTTEBORN et al. 1991). In fact, the proportion of uprooted trees in Babia Góra is one of the lowest observed in different types of temperate and boreal forests (SCHAETZL et al. 1989, LERTZMAN & KREBS 1991, ULANOVA 1991). The dominance of standing dead trees points to competition for light, biological factors (insects, fungi), and possibly air pollution as the main causes of death (HYTTEBORN et al. 1991).

The tendency of trees to uproot is greatest in intermediate size classes. PETERSON & PICKETT (1991) obtained similar results in a Pennsylvanian hemlock-hardwoods forest. However, these results differ from those obtained for spruce in northern Sweden (JONSSON & DYNESIUS 1993), where the probability of uprooting was higher for thicker trees. In Babia Góra forest many thick spruces are probably infected with wood-rotting fungi, which as in other areas promote stem breakage in contrast to uprooting (WEBB 1988, PETERSON & PICKETT 1991, MATLACK et al. 1993).

Uprooted and broken trees show different spatial arrangements. The former trees occur in clumps of different size while the latter are randomly distributed. It indicates that trees uproot only under certain soil conditions, which influence the strength of root anchorage. Clumped distribution of uprooted spruces was also noted in northern Sweden (JONSSON 1990).

The time elapsed since tree death ranged from several to more than 100 years, depending on the class of decomposition. The rate of CWD decomposition obtained in this study refers to large trees (dbh > 30 cm). The death of smaller spruces could not be determined with the same accuracy with the growth release method, as their influence exerted on the neighbors is relatively weak.

Thanks to the detailed description of logs in consecutive stages of decomposition it is possible to compare results from Babia Góra to those of HYTTEBORN et al. (1991) (Tab. 5). The log surfaces became marked with small and shallow crevices about 20 years after tree death at both localities. For further decomposition the similarity does not hold. Generally, decomposition of CWD on Babia Góra takes longer than in central Sweden.

On the other hand, CWD disappear faster in subalpine forests of Babia Góra than in boreal forests of northern Sweden (DYNESIUS & JONSSON 1991, HOFGAARD 1993 [b]). At high latitudes it takes nearly 200 years for a log to completely vanish from the soil surface,

Table 5. Comparison of the decomposition rates of spruce logs in subalpine forest of Babia Góra and in spruce forests of central and north Sweden.

Tabelle 5. Vergleich der Zersetzungsraten von Fichtenstämmen im subalpinen Fichtenwald von Babia Góra mit denen zentral- und nordschwedischer Fichtenwälder.

Babia Góra – Sweden 59° 53' N[1]				Babia Góra – Sweden 65° 35' N[2]			
class of decomposition		years		class of decomposition		years	
Babia Góra	Sweden	Babia Góra	Sweden	Babia Góra	Sweden	Babia Góra	Sweden
I.1	2	1–7	3–5				
I.2	3	6–13	6–10	I	1 + 2 + 3	1–13	< 22
I.3 + II	4	8–19	11–20	II	4	8–20	–
III	5	20–40	21–30	III + IV	5	20–60	45, 94
IV + V	6	30–60	31–40	V + VI	6	35–80	> 134, > 164
VI + VII	7+8	45–110	41–60	VII	7	65–105	85–174
VIII	9	> 80	61–70	VIII	8	> 80	< 119, > 134

[1] HYTTEBORN et al. (1991); [2] DYNESIUS & JONSSON (1991)

which is probably due to cold climate. It is worth noting that logs in North Sweden decompose more slowly than on Babia Góra in spite of their smaller diameters.

It has been shown by several studies that the breakdown of subalpine spruce stands on Babia Góra and in the Tatras has accelerated recently. A very high increase in CWD of up to 80% was noted on the northern slope of Babia Góra in the years 1984–1994 (Tab. 5, JAWORSKI & KARCZMARSKI 1995). In the Kotlový Zl'ab reserve (West Tatras) the amount of CWD in 1988 was 50% higher than in 1968 (Tab. 5, KORPEL' 1993). This trend is also revealed in the present study, where more than half of CWD present in 1993 originated in the 20 previous years and is now in classes I and II of decomposition. In no way could such quantities be balanced by the disappearance of logs, as 20 years make at least one-fifth of the whole time required for a spruce log to disappear.

While the intensity of stand breakdown increased recently, trees with large diameters also increasingly died. In the 1970's many trees died by natural thinning of young and thin trees, as can be concluded from dbh structure of stems in subclass I.3 of decomposition. In the 1980's more and more large trees died (subclasses I.1 and I.2). One could suppose that more thin snags and logs in subclass I.3 could be the result of the higher rate of their decomposition than of thick stems. This can be precluded as recently dead trees were classified according to the state of twigs and branches. It is reasonable to assume that the falling off of twigs and branches is independent of the diameter of snag or log they extend from.

The shift in mortality toward large trees reflects a change of causal factors. Elimination of thin spruces is usually a result of competition for light in a dense stand (self-thinning), whereas mortality of dominant individuals has different causes. Ageing is one possible explanation, as many trees exceeded 200 years (ZIENTARSKI 1976, JAWORSKI & KARCZMARSKI 1989). Once old stands have started to decrease in density (nearly 30% of area was in gaps in 1987, HOLEKSA 1998) more and more trees are likely to be exposed to wind gusts and deposition of snow and rime. This interpretation of breakdown supposes feedback in mortality, which can result in large area dieback of stands.

An alternative explanation of mortality could involve air pollution, as its effects act highly selectively on old trees. GRODZIŃSKA et al. (1990) and CAPECKI (1994) point out high concentrations of heavy metals in mosses and seasonally (in winter) high concentrations of sulphur dioxide and fluorine in the Babia Góra massif.

The diminishing frequency of thin logs from class IV of decomposition onward is the result of their faster decomposition and does not reflect lower mortality rates in the past. Thin logs are probably colonised faster by arthropods, which easily reach their central parts. Important is also the higher surface to volume ratio in thin logs (GRAHAM & CROMACK 1982, HARMON et al. 1986 and 1987).

There have also been changes in the spatial pattern of stand breakdown during the last 3 decades. In the 1960's and 1970's a thinning of stands smaller than 0.5 ha prevailed, which is indicated by the clumped distribution of dead trees in classes I.3, II and III of decomposition. Later intensive stand breakdown occurred over the whole area investigated, which is reflected in the random distribution of dead trees in subclasses I.1 and I.2.

The shift in mortality toward large trees, changes in the spatial pattern of stand breakdown during the last few decades, and the intensity of recent tree death nearly two times higher than the growth of trees probably reflect the tendency of the whole stand to enter the breakdown stadium. This process progresses simultaneously with the slow enlargement of the total gap area (HOLEKSA 2001).

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