



DOWN DEAD WOOD IN A FOREST – STILL AN OBSTACLE TO FOREST MANAGEMENT OR ALREADY AN ECOLOGICAL ISSUE?

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Abstract

This paper consists of three complementary sections, preceded by a short review of various Polish publications. The discussed sections cover: I. Method of measuring down dead wood (DDW) in a forest, II. An estimation of DDW resources in stands which are managed and of uneven-age, III. Suggestions for DDW management in managed forests – a look at the results of the suggestions made 10 years ago. The first section is a review of the main assumptions of the American approach to measuring DDW. The second section presents an evaluation of DDW resources in the three Forest Promotional Complexes of Puszcza Białowieska, Bory Lubuskie, Bory Tucholskie. An analysis of the correlations is included. The third and final part offers a critical look at the implementation of the recommendations made 10 years ago by the authors of the project. These were recommendations for, what were at that time, new principles of handling DDW in Polish forests.

Key words

down dead wood • method of measurements • Forest Promotional Complexes • forest management • dead wood volume

Introduction

In keeping with the format of this jubilee volume, this is a retrospective paper, a journey back to the years of 2000–2002. It was during this time period that a team of naturalists and geographers¹ of the then, Department of Geoecology at the Polish Academy of Sciences Institute of Geography and Spatial Organization headed by Professor Alicja Breymeyer, were working to complete a task entitled “Dead wood and its ecological functions in managed forests and forests reserves within

selected Forest Promotional Complexes”. The task was itself part of a project entitled “The basics of sustainable forest management in Forest Promotional Complexes”, coordinated by Professor Kazimierz Rykowski of the Forest Research Institute (Rykowski 2005).

It is worth remembering that at the time the project was being carried out, things were entirely different. There was a difference in the geopolitics and legal issues, but the biggest difference was in the mindset of the community. Forest Promotional Complexes were just starting out and experiencing their initial difficulties. The breaking ground concepts of ecological forestry or sustainable development divided rather than brought people together. Some perceived the concepts as an

¹ Team members: Prof. Alicja Breymeyer – Head of project, Prof. Marek Degórski, Assoc. Prof. Jerzy Solon, Assoc. Prof. Ewa Roo-Zielińska, Dr. Jacek Wolski.

impending catastrophe while others uncritically accepted the concepts.

This paper consists of three complementary sections, preceded by a short review of various Polish publications. The discussed sections cover: I. Method of measuring down dead wood (far as DDW) in a forest; II. An estimation of DDW resources in stands which are managed and of uneven-age; III. Suggestions for DDW management in managed forests – a look at the results of the suggestions made 10 years ago. This first section is a review of the main assumptions of the American approach to measuring DDW. The American theoretical foundations and recommendations for field work still remain the basis of all linear methods used for determining wood necromass on the forest floor. The second section presents an evaluation of DDW resources in the three Forest Promotional Complexes of Puszcza Białowieska, Bory Lubuskie, Bory Tucholskie. An analysis of the correlations is included. The third and final part offers a critical look at the implementation of the recommendations made 10 years ago by the authors of the project. These were recommendations for, what were at that time, new principles of handling DDW in Polish forests.

State of the art – yesterday and today

Let us start by reviewing the state of research in the 1990's, in our area of interest, in Poland. It is also important to look at the approach naturalists and foresters took to these issues in the late 1990s. Data on the actual resources of DDW in various types of managed and natural forests in Poland were less than scarce. Information about the broadly defined ecological importance of DDW was mainly derived from works by American, Canadian, and Scandinavian authors (e.g. Maser & Trappe 1984; Harmon et al. 1986; Maser et al. 1988; Samuelsson et al. 1994; McMinn & Crossley 1996), as intensive research had been carried out in these countries for several decades (Caza 1993; Lassetre 1999; Laudenslayer et al. 2002; Solon 2002). In Poland, DDW was generally considered to be an economic loss, an increased fire hazard or a breeding area for secondary pests and disease (Piotrowski & Wołk 1975). The focus was on forest phytopathology, saprophyte succession (Tracz 1980), and determination of the rate of decomposition. Investigations undertaken by the Białowieża

Geobotanical Station of the University of Warsaw (Faliński 1978; Masalska 1997), research co-ordinated by J. Gutowski², and a Polish-American research programme on “Patterns of coarse woody debris accumulation and decay on the forest floor of old growth in Białowieża Forest (Eastern Poland) and Hiawatha National Forest (Northern Michigan) – comparative study of protected and managed stands” completed in 2001 (Mroz et al. 2001) were exceptions to the rule. Papers published in forestry- and ecology-related journals were few and far between (Wesołowski 1993; Buchholz & Osowska, 1995; Ciapała & Holeksa 1997; Holeksa 1998; Zielonka & Niklasson 2001; Bobiec 2002; Wolski 2002, 2003), as were popular science publications (Kawecka 1995; Orczewska & Szwedo 1996; Borusiewicz 1997; Hilszczański 1997; Gutowski et al. 2002). There were no comparisons made between different types of forests. There were also no methodological papers on techniques for determining the volume of DDW of various diameter classifications. This situation was not in the least improved by the inclusion, in the official guidelines on ecology-based forest management issued by the State Forest Directorate, of only very vague suggestions to leave intact certain old trees until their biological death and to leave intact selected dead trees, particularly those with hollows.

Over the following decade, interest in DDW definitely increased among Polish scientists. The scientists' approach to this topic also changed. Notable achievements in this period primarily include extensive international research programmes. The biggest was the *BioSoil* project, concerned with carrying out inventories of the soil characteristics and biodiversity, at level 1 permanently monitored sites in forests. Determination of DDW volume was carried out as part of the *BioSoil Forest Biodiversity* module (Czerepko 2008). Another example was the project “Old trees and dead wood in forest ecosystems in Poland”. This project involved fieldwork carried out on a total of 120 sampling plots representing forest types commonly found in Poland and Europe. The project was part of the FINE (Forest Indicators for Europe) initiative (OldWood module). The co-ordinating

² The unpublished paper “Saproxylic beetles as an indicator of ecosystem disturbance in mesic coniferous forests” contains the results of the measurements of dead wood volume at plots in Puszcza Białowieska, Biebrza National Park, Bory Tucholskie, Puszcza Kozińska, and Świerklaniec Forest Inspectorate.

institution was the Polish Society for the Protection of Birds. Funding was provided by UNDP GEF/SGP and the Birdlife European Forest Task Force (Bobiec & Stachura-Skierczyńska 2007).

The review of various publications³ was not optimistic. Over the last 5-10 years, leading Polish nature journals have published only a handful of articles concerned solely with DDW. Only a few of those included evaluations of DDW resources or measurement methodology. The measurements were carried out in protected areas, such as the Upper Silesia area (Maślak & Orczewska 2010) and the city of Łódź (Pawicka & Wozniowa 2011). Other topics discussed were predominantly ecological (Holeksa & Maciejewski 2009). These topics focused particularly on the usefulness of wood necromass as a microhabitat for various animal groups (Skłodowski 2003; Bochynek & Drozdowicz 2011; Hilszczański et al. 2011), or were related to decomposition of dead wood matter (Bujoczek 2012).

Among popular science publications, "A tree's second life" (Gutowski et al. 2004) merits special attention. In an easy-to-understand manner, this book presents a wide range of issues related to dead wood (see also Sokołowska 2005; Piotrowski 2010 and others).

Method of measurement of down dead wood in a forest

Classification of DDW

Measurements of DDW resources take into account woody material lying on the forest floor. Such material includes fallen boles, stumps, branches, tree tops, roots (as rootstock and separate roots) and torn away fragments (e.g., those struck by lightning or which fell during a wind storm). The inventorying involves both fresh and nearly completely rotten pieces. The exception is debris decomposed to the point where measurement is not possible; where the piece has become part of the organic soil horizon. It does not matter what factor (of what origin, nature and consequences) led to the biological death of the tree. Broken and uprooted trees, diseased and weakened individuals,

those hit by lightning, felled by humans and, finally, those that have succumbed to physiological old age are all subject to measurement. The only types of material excluded are bark fragments separated from the main woody bulk, cones, all parts of ground cover plants, and pieces deliberately disturbed as during forest management activities.

There are, however, considerable differences regarding the cut-off value separating: fine (small) woody debris (fine fuel, fine woody detritus – far as FWD) and coarse woody debris (far as CWD). The cut-off value refers to measurements, not to division into diameter classes. Cut-offs for CWD have included piece diameters: >0.64 cm (Reed & Mroz 1997), >2.5 cm (Harmon et al. 1986), >7.1 cm (Hilbruner & Wordell 1992), >7.5 cm (Brown 1974; *Vegetation...* 2010), >8 cm (*Biodiversity...* 1995), >10 cm (Harmon & Sexton 1996; Lofroth 1998; Marshall et al. 2000; Chao et al. 2008), >15 cm (Sollins 1982; Davis 1998) or >20 cm (Harmon 1992). Many papers omit smaller material (FWD) from analysis or do not consider such material valuable.

There is also controversy over the classification of standing dead trees. Some papers⁴ do include snags (Harmon et al. 1986; Caza 1993; Davis 1998), while others do not (Brown 1974; Hilbruner & Wordell 1992; *Biodiversity...* 1995; Stevens 1997; Lofroth 1998; Marshall et al. 2000; *Vegetation...* 2010; *Field Manual...* 2010). It seems that the specific characteristics of microhabitats, differences in nutrient circulation as well as light and moisture conditions, different rates of decomposition, and the sequence of colonisation by animal and plant species clearly indicate a need to distinguish two separate categories.

What is then the proper way to define DDW? There are numerous definitions quoted in the literature (e.g. Harmon & Sexton 1996; Stevens 1997; Davis & Nemeč 2002; *Field Manual...* 2010). Based on these definitions and my own observations, I have come up with my own definition. DDW may be defined as all pieces of decayed (as a result of roots no longer having contact with the substrate, or disintegration of the pulp material) wood and woody matter of various sizes, which have not been deliberately moved, but were left

³ The review took into account the following journals (all issues published in the last 5 or 10 years): *Sylwan*, *Leśne Prace Badawcze*, *Folia Forestalia Polonica – Ser. A Leśnictwo*, *Acta Scientiarum Polonorum – Ser. Leśnictwo i Drzewnictwo*, *Dendrobiology*, *Polish Journal of Ecology*, *Chrońmy Przyrodę Ojczyzny*, *Ochrona Środowiska i Zasobów Naturalnych*, and *Aura*.

⁴ This article does not mention studies concerned exclusively with standing dead wood because a different measurement methodology is used, making it impossible to compare the results (e.g. Harrod et al. 1998; Bate et al. 1999).

on the forest floor due to natural or anthropogenic causes. These pieces provide a living environment for plants and animals and a source of nutrients contributing actively to the development of soil.

Theoretical foundations

Two methodological approaches, differing both in their theoretical assumptions and field work arrangements, are used for measurements of DDW resources – particularly its volume, biomass and numbers. The two approaches are: area methods (circular, relascope-based), and linear methods. The latter is the subject of the present paper (Ducey & Gove 2000; Lutes 2002). Other methods are used to a much lesser extent. Both the direct (Williams 2005; Woodall & Westfalt 2008; Pesonen et al. 2009; Gove et al. 2012) and indirect measurement techniques, including radar imaging (Huang et al. 2009) and airborne laser scanning (Pesonen et al. 2008) are used.

The original concept of line intersect sampling⁵ was developed primarily to cater to the needs of the fire prevention service, and strictly for when taking inventories. The authors of the original concept of line intersect sampling were Warren with Olsen (1964) and Van Wagner (1968). The measurement techniques they suggested can be used with very diverse objects, differing both in area, and natural, economic or administrative characteristics. The use of these techniques is confirmed by decades of research carried out all over the world (Harmon et al. 1986; Caza 1993; Davis 1998). The finding of multiple similarities between these methods and the algorithm for the construction of large-area forest measurement methods (Bruchwald 1999) also confirms the use of these techniques.

The statistical unit is a sampling plot described with such metrics as DDW volume, patterns of its presence on the forest floor, degree of decomposition and percentage contributions of dominant tree species. However, determining the appropriate size for a plot is a problem. A minimal sample size must meet the criteria of appropriate precision and representativeness. The problem is that the determination of the sample size requires previous knowledge of the distribution and variability of the above-mentioned metrics. Pilot studies of

small random samples can provide these distribution and variability. This example clearly shows that before actual measurements are undertaken, their theoretical foundations need to be learned and understood. In this way, mistakes can be avoided at subsequent stages of the research project. The research can also be tailored to the requirements and needs of the author.

The theoretical assumptions underlying the line intersect method are based on the relation between a variable⁶ (y_{ij}) describing a piece of DDW j to the probability (P_{ij}) of the piece being crossed by an intersecting line i :

$$y_i = \sum_{j=1}^m \frac{y_{ij}}{P_{ij}} \quad (1)$$

In order to determine the probability that a piece of DDW of length l_j will be transected by line i , a hypothetical plot A needs to be marked containing a rectangle of sides L and W , where L is also the maximum length of the intersecting line i (axis of symmetry of the rectangle LW), and W is longer than the longest piece of DDW (Fig. 1). The probability of an intersection occurring at point M_{ij} is the mathematical product of two events: (a) point M_{ij} must be in the rectangle LW and (b) the intersection ensures that M_{ij} is in the rectangle LW (Marshall et al. 2000).

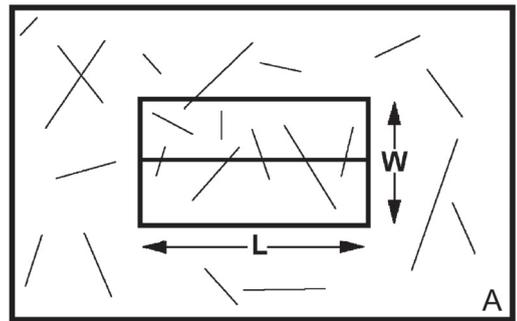


Figure 1. Hypothetical image of population (A) and sample (rectangle LW).

The probability of event (a) describes the ratio of “sample” size to “population” size (LW/A). Event

⁵ Several years later Brown (1974), rightly assuming that the line is actually a type of intersecting plane perpendicular to the earth’s surface, proposed the name *planar intersect method*. This proposal did not gain popularity in the literature.

⁶ Most of these calculations are based on relationships (1), which is not defined in any unit. To avoid increasing the number of parameters defined in the article, subsequent formulae will use one symbol (y_i), which will refer to: volume in m^3/ha (8), number of pieces in pieces/ha (10), mean length in m/ha (11) and surface area in m^2/ha (12).

(b) depends on the inclination angle (θ_{ij}) of the axis of the woody piece to the ground surface (from 0 to 90°, or 0- $\pi/2$ radians) and the length of the segment (m_{ij}) beginning at M_{ij} and ending at the intersecting line at a right angle to it (Fig. 2). For the basic condition regarding the location of M_{ij} to obtain: $0 \leq m_{ij} < W/2$. These assumptions are rendered in the denominator, which represents the product of maximum values of the above ranges:

$$\frac{?}{\frac{W}{2} \times \frac{\pi}{2}} \quad (2)$$

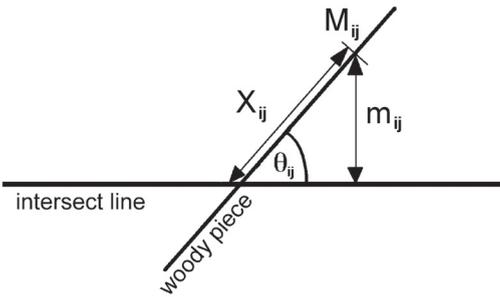


Figure 2. Directions of intersect lines and location of sample elements.

If $\theta_{ij} = \pi/2$, then $0 < m_{ij} \leq l_{ij}/2$. The same condition must be met for distance X_{ij} between point M_{ij} and the earth's surface, measured along the axis of the woody piece, i.e. $0 < X_{ij} \leq l_{ij}/2$. If either of the above conditions is not met ($m_{ij} > W/2$, $m_{ij} > l_{ij}/2$, $X_{ij} > l_{ij}/2$), then in the event of a location change of a piece elevated above the intersecting line, point M_{ij} may fall outside the borders of rectangle LW . After substitution of the value of X_{ij} calculated according to the formula for the length of a cathetus ($m_{ij} = X_{ij} \times \sin \theta_{ij}$), we have:

$$m_{ij} \leq \frac{l_{ij}}{2} \times \sin \theta_{ij} \quad (3)$$

The area under the curve (3), where $0 < \theta_{ij} < \pi/2$, is actually $l_{ij}/2$, as mathematically proved by Marshall, Davis and LeMay (2000). Thus, the ultimate probability P_{ij} of the co-occurrence of events (a) and (b) amounts to:

$$p_{ij} = \frac{L \times W}{A} \times \frac{\frac{l_{ij}}{2}}{\frac{W}{2} \times \frac{\pi}{2}} = \frac{2 \times L \times l_{ij}}{A \times \pi} \quad (4)$$

The above considerations still do not answer the question of how actual resources of DDW should be calculated. The key to further analyses is the formula (1), which takes the following form:

$$y_i = \sum_{j=1}^{m_i} \frac{v_{ij}}{P_{ij}} \quad (5)$$

where the value of the variable v_{ij} is the volume (in m^3) of a DDW piece j crossed by the line i . Calculations of volume are based on Huber's formula for a cross-section through the middle of a piece (Harmon & Sexton 1996; Bruchwald 1999), where the length of a piece of DDW l_{ij} (in metres) is multiplied by its cross-section area $g_{ij/2}$ (in cm^2), calculated from its diameter $d_{ij/2}$ (in centimetres). Huber's original formula requires that the diameter be measured at the middle point of the length of a woody piece. The specifics of the method under discussion, however, have forced a certain modification and the diameter is taken at the point of the actual intersection of the piece by the line ($d_{ij/2} = d_{ij}$). Thus, the formula becomes:

$$v_{ij} = g_{ij/2} \times l_{ij} = \frac{\pi}{10000} \times \left(\frac{d_{ij/2}}{2} \right)^2 \times l_{ij} = \frac{\pi}{40000} \times d_{ij/2}^2 \times l_{ij} = \frac{\pi \times d_{ij}^2 \times l_{ij}}{40000} \quad (6)$$

where the coefficient 10,000 is used to convert the area units from cm^2 to m^2 . The total resource (volume) of DDW y_i (in m^3/ha) in area A can then be calculated by substituting already known values into the formula (5):

$$y_i = \frac{\left(\sum_{j=1}^{m_i} \frac{\pi \times d_{ij}^2 \times l_{ij}}{4 \times 10000} \right)}{\left(\frac{2 \times L \times l_{ij}}{A \times \pi} \right)} = \frac{\pi^2 \times A}{80000 \times L} \times \sum_{j=1}^{m_i} d_{ij}^2 \quad (7)$$

and, assuming that area A is 1 ha (10,000 m^2), it finally follows that:

$$y_i = \frac{\pi^2}{8 \times L} \times \sum_{j=1}^{m_i} d_{ij}^2 \quad (8)$$

For branches and twigs, which are assigned to their respective size classes with a diameter according to, it should be assumed that

$$\sum_{j=1}^m d_{ij}^2 = m \times d_{sr}^2 \quad (9)$$

where:

m – is the number of DDW pieces,

d_{sr} – is the representative diameter of each size class.

In order to determine the respective representative diameters, individual size classes need to be divided into smaller ranges and the frequency of occurrence of particular diameters needs to be estimated in the field (Van Wagner 1982). An inferior, but simpler, solution is to find the median in each range, and calculate average values of variables according to the formula for calculating the arithmetic mean of a stem-and-leaf plot. A mean so calculated, differs from that calculated from the unitary values because of differences between medians of classes and means of units.

Formula (1) can also be used to calculate other variables serving as metrics of DDW resources (Marshall et al. 2003; Wolski 2003). The most commonly used of these comprise (for $A=1$ ha):

1. number of DDW pieces (pieces/ha):

$$y_i = \frac{10000 \times \pi}{2 \times L} \times \sum_{j=1}^{m_i} \frac{1}{l_{ij}} \quad (10)$$

2. mean length of a DDW piece (m):

$$y_i = \frac{m_i}{\sum_{j=1}^{m_i} \frac{1}{l_{ij}}} \quad (11)$$

where m_i is the number of all DDW pieces crossed by the intersect line i ;

3. area occupied by DDW (m^2 /ha):

$$y_i = \frac{50 \times \pi}{L} \times \sum_{j=1}^{m_i} d_{ij} \quad (12)$$

Before measurements of specific parameters describing a statistical unit are undertaken, it is recommended that a required level of precision is defined. If the standard deviation of the population is known, a minimum sample size can be determined (in our case, it is the number of lines in a given unit of area). Minimum sample size will ensure that the maximum error of estimation of the parameter in question from the population will not exceed a pre-determined value, equal to half of the length of the confidence interval. For

calculations of DDW volume, it appears advisable to express the value of maximum error as a percentage (percentage error) rather than as a unit of weight or volume. Unfortunately, the standard deviation of the population is usually not known before a study has commenced, so sample size has to be arrived at by repeated approximation. The problem of the determination of a minimum sample size, required for estimating a given parameter from a population for a known precision level, is analysed in detail by Bruchwald (1997).

There is no final answer from the literature, to the questions concerning how many intersect lines there should be per unit of area and how long these lines should be. Considerable discrepancies on this issue were found between various authors. Suggestions include: one equilateral triangle or three independent lines (3×30 m) per hectare (Parminter 1998b), one equilateral triangle (3×30 m) per 20 ha (McRae et al. 1979), 304 m per 20 ha (Brown & See 1981), and 960 m per 20 ha (Vegetation... 2010). Brown (1974), de Vries (1973) and Pickford and Hazard (1978) suggest that some flexibility is needed and that the choice should vary depending on the situation in the field or the goals of study. For example, lines may be shorter in areas with a predominance of branches and twigs, compared to measurements of CWD and boles.

With sampling results ready, the researcher can make conclusions regarding the values of the random variable parameters in the general population. Here, the basic problem is to choose a statistic based on the sample that will provide the best estimate of the parameter in the population. The fundamental characteristics of a good estimator are: lack of bias (the expected value of the statistics from the sample equals the true value of the parameter in the general population), and efficiency (the sample distribution has the least possible variance) (Zasępa 1972; Bruchwald 1997). The most commonly used estimators are the sample arithmetic mean (13) and standard deviation (14):

$$\bar{y} = \frac{\sum_{i=1}^n y_i}{n} \quad (13)$$

$$S_{\bar{y}} = \sqrt{\frac{\sum_{i=1}^n y_i^2 - \frac{\left(\sum_{i=1}^n y_i\right)^2}{n}}{n \times (n-1)}} \quad (14)$$

Apart from point estimation, the method of interval estimation is also popular. With this method, the estimated population parameter should fall within the range of the confidence interval for a confidence level of $1-\alpha$. Here is a confidence interval for a population mean μ_y , where the estimator is the sample arithmetic mean:

$$\mu_y \in \left\langle \bar{y} - t_{n-1, \alpha/2} \times S_{\bar{y}}; \bar{y} + t_{n-1, \alpha/2} \times S_{\bar{y}} \right\rangle z P = 1 - \alpha \quad (15)$$

where $t_{n-1, \alpha/2}$ is the critical value for a Student's t distribution with the number of degrees of freedom $k=n-1$, and the sample mean is normally distributed. This is a random interval whose boundaries are dependent on sample data. The random variable is interval length and interval boundaries, while the population parameter is a constant. The t distribution, just like a normal distribution, is symmetrical, but its outline changes with sample size. The t distribution being indirectly dependent on the number of degrees of freedom.

In order to see a more clearly illustrated view of the above theoretical assumptions, and calculations of sample variables as well as estimations of population variables, the readers may refer to an earlier paper which presents the calculations of DDW volume at a plot set up in the "Źródłiskowa Buczyzna" reserve in the Forest Promotional Complex Lasy Puszczy Bukowej i Goleniowskiej (Wolski 2002: 40).

Field measurements

"Dead wood and its ecological functions in managed forests and forest reserves in selected Forest Promotional Complexes", is the title of the project mentioned at the beginning of this paper. The project employed the following procedure by Brown (1974):

1. Mark off parallel lines 5-10 units of distance apart from each other in the field, and then mark central sampling points along these lines 2-5 distance units apart (proportions are important while unit length will depend on the circumstances). Mark the points in a systematic manner (e.g. as a geometric network of points), with the exception of the first one, which is usually placed intuitively within the field.

2. Randomly choose the direction of the intersect line at one of the six 30° angles between 0° and 150° from the first central point, and plot the line (Fig. 3). The rationale behind choosing a direction at random is because of the random distribution of DDW on the forest floor.
3. Inventory all DDW pieces crossed by the intersecting line: those with a diameter >7.6 cm along the entire line length; those in the range of 2.5-7.6 cm within 0-3 m; and those in the range of 0-0.6 cm and 0.6-2.5 cm within 0-1.8 m (Fig. 3). Branches and twigs (<7.6 cm) are assigned to size classes with a diameter gauge, while coarser debris is measured to an accuracy of 0.1 cm^2 .
4. Identify the tree species (in the case of boles and CWD). Estimate the percentage contribution of 2-3 dominant species for each size class (branches and twigs). These actions are done to calculate specific gravity, and subsequently, total DDW biomass.
5. Measure the length of DDW pieces and determine the stage of decomposition (usually for coarser material).

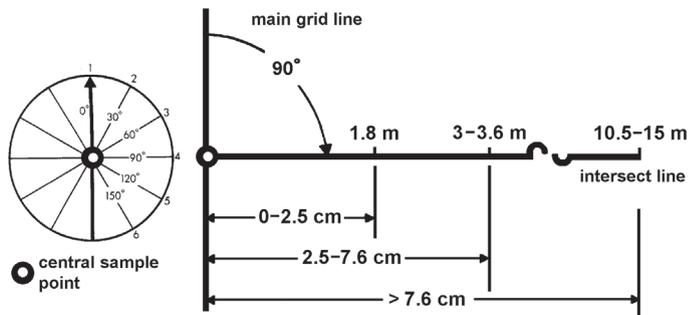


Figure 3. Position parameters of woody debris lying over intersect line.

Determining the decomposition stages of DDW is of major importance during field work. A few classification systems have been developed over the last several decades. These systems differ considerably in the degree of complexity and range of use. One of the first classifications, designed to match the needs of the American fire protection services, was developed by Brown (1974). It was a very simplified division of sound wood and rotten wood (the latter

⁷ Detailed measurement principles of DDW pieces are described in the literature and in forest inventory guidelines (Warren & Olsen 1964; Van Wagner 1968; Brown 1974; Hilbruner & Wordell 1992; Marshall & Davis 2002; Wolski 2002; *Field Manual...* 2010; *Vegetation...* 2010).

was described as pieces that look... "punky or can be easily kicked apart"). Then followed a three-degree scale (Davis 1998), and then a five-degree one, based on wood structure, bark status, the presence of small twigs and overgrowing roots, the shape of a cross-section, portion of the log on the ground, and wood colour (Maser et al. 1979) with subsequent modifications (e.g. Chao et al. 2008). Some papers add biological indicators, such as being covered with moss, lichen, fungi, the presence of invertebrates or white and brown rot as well as the degree of sapwood degradation and heartwood decomposition (Harmon & Sexton 1996; Orczewska & Szwedo 1996). I believe (Wolski 2002) the five-stage classification is optimal. The three-stage system fails to account fully for the diversity of observed phenomena, and more complex divisions are difficult to employ in the field.

The problem of fragmentation of thicker pieces of wood (for example in areas where wild boars live) is very rarely discussed. Torn-away pieces are often ignored during measurements, which may seriously influence the result as their contribution to the total volume of overground detritus and may actually exceed 50% (Harmon & Hua 1991).

Additional correction factors devised by Brown (1974)⁸ should also be discussed. The first of these is an angle correction factor to adjust for the angle λ_{ij} between the axis of a DDW piece and the horizontal plane. The angle correction factor is calculated as $1/\cos \lambda_{ij}$. At a 10° angle, however, the correction factor is just 1.01, only reaching a value of 1.1 at 25°. The measurement error ($1-\cos \lambda_{ij}$) at small angles also indicates that such adjustments are often unnecessary, as the error again exceeds 10% at angles greater than 25°.

Another correction adjusts for the slope of the ground. This correction is sometimes used to calculate the actual (reduced) length of the intersect line, or its projection on the horizontal plane:

$$\sqrt{1 + \left(\frac{\text{slope}(\%)}{100} \right)^2} \quad (16)$$

where a slope of 100% corresponds to 45°. According to McRae, Alexander and Stocks (1979) and Parminter (1998a), corrections need to be

⁸ Early concepts of the transect method, presented a simplified model of reality. For example, it was assumed that all DDW pieces lie flat on the ground and the slope of the ground is 0°.

made when the value is greater than 10%, i.e. for slopes exceeding 20°.

Instructions on measuring the height of DDW pieces (vertical characteristics) and the depth of duff (fermentation horizon) were also provided by Brown (1974). In my opinion, these additional data are superfluous if the goal of stock-taking is to determine DDW volume.

Most of the above methodological considerations have to do with pieces that have a round cross-section. Oval, semi-oval, and irregular woody pieces need to be classified separately as the measurement technique is different. The actual length of the DDW piece crossed by the intersect line (DDW width, W_{ij}), and mean height (H_{ij}) of the piece at this point, need to be measured. The results are to be interpreted as the sides of a rectangle, and recorded as separate values (Marshall et al. 2000; *Field Manual...* 2010):

$$v_{ij} = \frac{W_{ij} \times H_{ij}}{L} \times 10000 \quad (17)$$

where both dimensions of the rectangle are measured in metres, and the 10,000 m²/ha coefficient ensures the result is expressed in appropriate units (m³/ha). A similar approach is followed by Reed and Mroz (1997), with the one difference being that they advocate formula (8) and suggest modifying only the diameter value:

$$d^2 = \frac{(W_{ij}^2 \times H_{ij}^2)}{2} \quad (18)$$

It is necessary to remember that various modifications of the original line-intersect method exist. All the modifications are based on the same theoretical foundations, but differ in the organisation of field measurements. The modifications particularly differ in assumptions regarding the distribution, length, and number of intersect lines per unit area. Apart from the arrangement described in this paper, other types of transects have been used, for example, L-shaped (Caza 1993; *Field Manual...* 2010), equilateral triangles (Delisle et al. 1988), and star-shaped with three lines crossing at a 120° angle (Davis 1998). According to Marshall, Davis and LeMay (2000) the total length of the lines is more important than the lengths of individual lines. This confirms the findings of previous studies (de Vries 1973; Pickford & Hazard 1978): if the lines are of equal lengths, their spatial arrangement is of little

importance. The lines can be separate segments or fragments of one transect. A very interesting analysis of results obtained using six different transect types was conducted by Nemec & Davis (2002). There are many more examples of such fine details that should be taken into consideration. Readers are advised to consult the comments presented as an FAQ list (Marshall et al. 2003) as well as the valuable observations concerning the possibility of overestimating the volume of finer material (<25 cm) and underestimating the contribution of pieces with the largest diameter (>50 cm) (Bate et al. 2009).

Despite such complexities, the line intersect method is still commonly used for stock-taking in forest ecosystems throughout the world (Tietje et al. 2002; Bobiec & Stachura-Skierczyńska 2007; Jönsson & Jonsson 2007; Chao et al. 2008; Pawicka & Woziwoda 2011). Models are also being developed to predict increases or decreases in DDW volume depending on: stand age, the after-effects of forest fire, or multiple variants of forest management practices (e.g. DEADWOOD model of Tinker & Knight 2001).

Estimation of down dead wood resources in managed stands where the stands are of an uneven age

Volume of DDW

It is worth looking at the diversity of DDW volume in the forest ecosystems around the world. In general, this parameter is a function of supply and decomposition rate, but in practice it is influenced by an array of factors, which are presented below.

Apart from climate zones and local climate, the microclimate of the forest floor also has a considerable influence on the amount of DDW. The microclimate itself is influenced by the degree of shading (canopy closure, species composition of forest stand, exposure to sunlight) of the forest floor, air flow levels (the species composition and proximity of shrubs and trees in the understory), and substrate moisture (interception of precipitation, ground water levels, substrate permeability). In some climatic zones, similar types of forests support much less DDW at dry cold sites than at moist cool sites. For instance, in the Canadian subboreal zone, the amount of dead wood was 44.1-159.2 m³/ha in stands of spruce vs. 36.2-268.4 m³/ha in stands of pine (Lofroth 1998).

A considerable and commonly known influence on tree mortality is exerted by geomorphic processes affecting slopes. The shifting or removal of mantle from rock surface (slide, downhill creep) is involved. Sometimes the presence of one specific horizon in the soil profile (e.g. a very hard orstein horizon) may have an adverse effect on trees with poor or shallow roots (Mroz et al. 2001).

The ecological health status of the forest stand is another important factor influencing the volume of DDW in a forest. This is related, among others, to the frequency of the disturbances in a natural stand's development; especially fires, flood, strong winds, and pest gradations. Differences in DDW volume attributable to different frequencies of these events may range from 60 m³/ha (*Picea mariana*, *P. canadensis*) to 390 m³/ha (*Tsuga heterophylla*) according to Lofroth (1998). It is also important to know what caused the DDW. A study in Northwest Russia showed the mean volume of dead wood shortly after a clear-felling and removal of timber to be 24 m³/ha, compared to volumes as high as 145 m³/ha at sites of "natural" disturbances (Krankina et al. 2001).

The frequency of improvement cutting and the type of felling may have a greater effect on dead wood volume than cutting intensity or harvesting yield (Aber et al. 1978, after Caza 1993). The volume of dead wood is much smaller in (a) areas often subjected to forest management practices, and (b) areas where clear felling and partial cutting is applied. This is attributable to: (a) low stand volume and not allowing trees to die naturally (slowly), (b) leaving mainly fast-decomposing fine material at felling sites, and (c) the heavy equipment which destroys the DDW on the forest floor, especially DDW at an advanced stage of decomposition (Gore & Patterson 1986; Spies & Cline 1988).

The volume of DDW (in particular the percentage of coarse fractions) and its decomposition rate are closely associated with stand age. Mean stand height has a much weaker effect (Harmon et al. 1986; Franklin et al. 1987; Harmon & Sexton 1996; Spetich et al. 1999). The rate of decomposition also varies with tree species, with up to ten-fold differences (Harmon et al. 1987; Mattson et al. 1987, after Lofroth 1998).

Two of the foremost researchers to demonstrate that the amount of dead wood increases with stand productivity, in a naturalist sense of the term, were O'Neill & DeAngelis (1981). Many researchers have also noted a higher annual dead

wood supply in coniferous stands (Harmon & Hua 1991). However, in view of a considerable diversity of factors responsible for the decomposition of woody material, such material is often not correlated with the amount of woody material available on the forest floor.

Research carried out within the *BioSoil* project found the mean volume of dead wood in Polish forests to be 9.6 m³/ha. All boles and thicker branches were removed from approximately 65% of the study plots. DDW and dead trees were found at approximately 45% of the plots, and stumps were present in more than 90% of the plots. It is important to note, though, that the measurement methodology used by the *BioSoil* project was different, and the forests under study were very diversified in terms of use patterns and conservation status (Czerepko 2008).

Plot characteristics

DDW volume was measured at six plots in three Polish Forest Promotional Complexes: Bory Tucholskie (1 plot), Bory Lubuskie (1 plot) and Puszcza Białowieska (4 plots) (Tab. 1).

The selected study areas had similar soil types and soil characteristics and basic phytosociological and floristic parameters. The forest communities where the plots were located, belong to the class *Vaccinio-Piceetea*, order *Cladonio-Vaccinietalia*, and alliance *Dicrano-Pinion*. Natural oligo- and mesotrophic coniferous forest communities were represented. There is a distinct predominance of pine in the forest stand and a ground cover composed of dwarf shrubs with mosses or grasses with mosses. Syntaxonomic differences can be seen at the level of association (*Leucobryo-Pinetum*, *Peucedano-Pinetum* and *Serratulo-Pinetum*) (Roo-Zielińska & Solon 2002). All plots were set up in managed forests representing a similar, medium-intensity pattern of use. Such a pattern is representative of this type of forested area in Poland. Stand age was the main differentiating criterion (37-154 years).

Within each plot, a total of 20 intersect lines, 10.5 m long each, were marked off. Central points were located along parallel transects located 30 m apart from each other. The total measurement area was approx. 0.7 ha. The finest (smallest) woody pieces (<0.6 cm) were just counted,

Table 1. Location and selected soil and botanical characteristics of experimental plots.

Site name	Bory Lubuskie	Bory Tucholskie	Puszcza Białowieska (742)	Puszcza Białowieska (493)	Puszcza Białowieska (520)	Puszcza Białowieska (521)
Forest inspectorate	Lubsko	Tuchola	Browsk	Białowieża	Białowieża	Białowieża
Forest district	Ciemny Las	Świt	Lacka Puszcza	Suche	Podcerkiew	Podcerkiew
Forest sections	223 h	66 i	742 b	493 Ag	520 Bh	521 Aa
Latitude N	51°44' 43"	53°33'08"	52°53'19"	52°41'32"	52°41'32"	52°41'32"
Longitude E	14°45'19"	17°53'29"	23°37'10"	23°43'42"	23°43'42"	23°43'42"
Altitude	119	147	109	120	120	120
<i>Pinus sylvestris</i> age	98	94	93	154	37	71
Forest community	<i>Leucobryo-Pinetum</i>	<i>Leucobryo-Pinetum</i>	<i>Peucedano-Pinetum</i>	<i>Serratulo-Pinetum</i>	<i>Serratulo-Pinetum</i>	<i>Serratulo-Pinetum</i>
Soil type	podzolic	rusty	podzolic	podzolic-rusty	podzolic-rusty	podzolic-rusty
Genetic horizons	O - AEes - Ees - Bhfe - C	O - AE - BfeBv - Bv - C	O - AEes - Ees - Bhfe - C	O - AE - BfeBv - Bv - BvC - C	O - AE - BfeBv - Bv - BvC - C	O - AE - BfeBv - Bv - BvC - C
Humus type	mor	moder-mor	mor	moder-mor	moder-mor	moder-mor
pH in humus horizon	4.23	4.08	4.74	4.53	4.44	4.34
Tree species in a1 layer	<i>Pinus sylvestris</i>	<i>Pinus sylvestris</i>	<i>Pinus sylvestris</i> <i>Picea abies</i>	<i>Pinus sylvestris</i> <i>Picea abies</i>	<i>Pinus sylvestris</i> <i>Betula pendula</i>	<i>Pinus sylvestris</i>
Tree species in a2 layer	no	<i>Betula pendula</i> <i>Fagus sylvatica</i>	<i>Quercus robur</i> <i>Betula pendula</i>	no	<i>Picea abies</i>	<i>Picea abies</i> <i>Betula pendula</i>

Source: according to Degórski (2002); Roo-Zielińska and Solon (2002).

Table 2. Number of dead wood pieces by diameter classes and decomposition stage.

Site name	0-0.6 cm	0.61-2.5 cm	2.51-7.6 cm	>7.6 cm					Total
				I	II	III	IV	V	
Bory Lubuskie	198	35	10	0	0	0	6	1	250
Bory Tucholskie	373	52	7	0	0	0	0	0	432
Puszcza Białowieska (742)	466	32	9	0	0	0	0	0	507
Puszcza Białowieska (493)	847	10	13	0	2	2	1	5	880
Puszcza Białowieska (520)	681	89	42	0	8	4	2	12	838
Puszcza Białowieska (521)	476	64	22	0	1	0	0	5	568
Total	3,041	282	103	0	11	6	9	23	3,475

thicker pieces (0.6-7.6 cm) were measured (length, thickness), and for pieces >7.6 cm, the stage of decomposition was additionally determined on a 5-stage scale (Maser et al. 1979). The findings were recorded in a form designed by the author (see: Wolski 2002: 38-39).

The conversion of DDW volume data (m^3/ha) into mass (t/ha) requires specific gravity data (kg/m^3). As pine (*Pinus sylvestris* L.) was a clear dominant, calculations for all plots involved this species only. The following specific gravity values were assumed (kg/m^3): 820 for freshly cut wood, 510 for air-dried wood with absolute moisture at 12-15%, and 490 for oven-dried wood⁹. The specific gravity of CWD decreases considerably as decomposition increases (Harmon & Sexton 1996; Hale & Pastor 1998; Harmon et al. 2000; Adams & Owens 2001). CWD lies in the open air for a number of years, especially pieces 2.5-7.6 cm in diameter that are not under the ground cover or in the soil. The above information makes it possible to predict that actual DDW mass will fall in between the figure calculated for air-dried wood (as a maximum) and that figure diminished by 30-50% (as a minimum).

Results

The distribution of DDW wood showed a very distinct pattern for different sized classes (Tab. 2). The number of pieces decreased as size increased.

There were also big differences among individual plots. Additionally, the amount of FWD decreased in older stands while the amount of coarse pieces increased noticeably (Fig. 4). A very high accumulation of material classified as the finest/smallest in size (<0.6 cm) at a plot in Puszcza Białowieska (493) appeared to be an isolated finding and not sufficient enough to disprove the above tendency.

At Puszcza Białowieska, no pieces with a diameter exceeding 7.6 cm were classified as fresh. There was a clear dominance of DDW representing the stage of the greatest decomposition (class V), which accounted for nearly a half of the total volume in this class size.

The total volume of DDW ranged from $5.11 \text{ m}^3/\text{ha}$ in Bory Lubuskie to $39.35 \text{ m}^3/\text{ha}$ in Puszcza Białowieska (493). This was nearly an 8-fold difference between extreme values (Tab. 3). The mass of DDW (air-dried) ranged between 2.42-20.07 t/ha. In practice, especially in plots with a large contribution of coarse material, these values could be even 50% lower, reaching approximately 1-10 t/ha. At plots with little or no material in the largest diameter class (Bory Tucholskie, Puszcza Białowieska 742, 521), there was a substantial contribution of the 0.6-2.5 cm size class pieces (Fig. 5). This appears important as FWD is not usually included in measurements or classified as organic matter of the forest floor. Such debris is often not classified as wood.

The area occupied by DDW on the forest floor was, by far, the largest in the plot (Puszcza Białowieska 520) supporting the youngest tree stand (nearly $1200 \text{ m}^2/\text{ha}$), compared to a nearly twice lower figure in a 70-year-old forest ($626 \text{ m}^2/\text{ha}$). In plots with +90-year-old stands (Puszcza Białowieska 742, Bory Tucholskie, Bory Lubuskie), the figures were approximately $300 \text{ m}^2/\text{ha}$, even though

⁹ No laboratory measurements of the physical properties of wood were carried out as part of the project and specific gravity values were based on the Wood Technology Institute's data ("Użytkowe gatunki drewna - vademecum", www.itd.poznan.pl) and the literature (Simpson 1993; *Forest Products Laboratory* 1999). The mass of concurrent, sparse species was calculated using the specific gravity of pine.

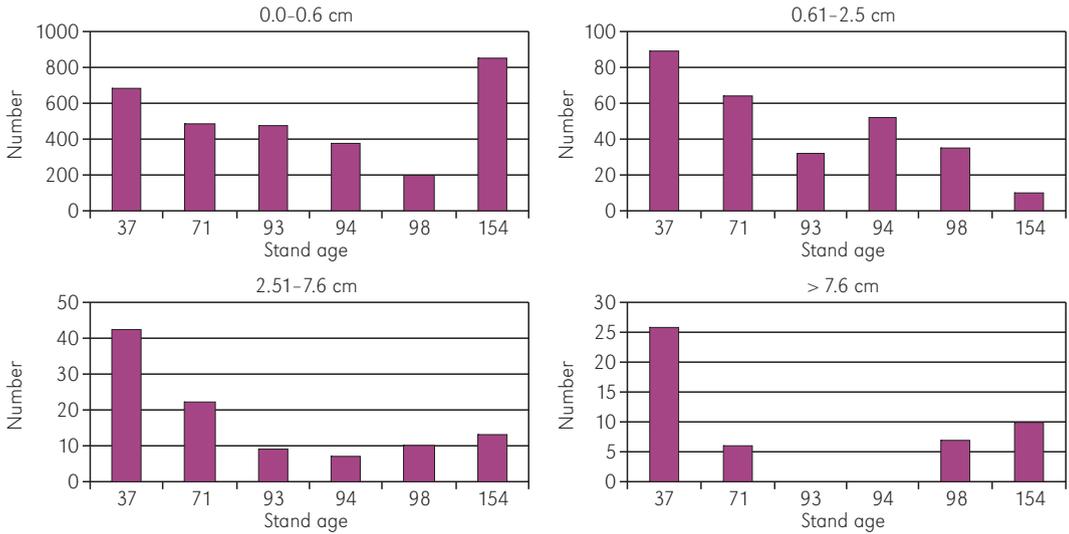


Figure 4. Number of dead wood pieces (Y axis) depending on stand age (X axis).

Table 3. Volume and mass of dead wood with standard deviation and 95% confidence interval (by diameter class).

Site name	Diameter class (cm)	Total by diameter class (m ³ /ha)	Standard deviation	Range (95% confidence interval)	Total (m ³ /ha)	Ovendry wood		Air dry wood		Fresh wood	
						Total by diameter class (t/ha)	Total (t/ha)	Total by diameter class (t/ha)	Total (t/ha)	Total by diameter class (t/ha)	Total (t/ha)
Bory Lubuskie	0.0-0.6	0.61	0.07	0.45; 0.77	12.12	0.30	5.94	0.31	6.18	0.50	9.95
	0.61-2.5	1.95	0.61	0.67; 3.23		0.95		0.99		1.60	
	2.51-7.6	2.25	0.96	0.24; 4.26		1.10		1.15		1.85	
	>7.6	7.32	4.61	-2.32; 16.96		3.59		3.73		6.00	
Bory Tucholskie	0.0-0.6	1.15	0.11	0.92; 1.37	5.11	0.56	2.32	0.59	2.43	0.94	3.89
	0.61-2.5	1.94	0.61	0.66; 3.23		0.95		0.99		1.59	
	2.51-7.6	1.66	0.63	0.33; 2.99		0.81		0.85		1.36	
	>7.6	0.00	0.00	n.d.		0.00		0.00		0.00	
Puszcza Białowieska (742)	0.0-0.6	1.44	0.18	1.07; 1.80	6.02	0.70	2.94	0.73	3.07	1.18	4.94
	0.61-2.5	1.33	0.32	0.66; 2.01		0.65		0.68		1.09	
	2.51-7.6	3.25	1.14	0.87; 5.63		1.59		1.66		2.67	
	>7.6	0.00	0.00	n.d.		0.00		0.00		0.00	
Puszcza Białowieska (493)	0.0-0.6	2.61	0.26	2.08; 3.14	30.48	1.28	14.93	1.33	15.54	2.14	24.99
	0.61-2.5	0.76	0.29	0.16; 1.36		0.37		0.39		0.62	
	2.51-7.6	4.21	1.86	0.30; 8.11		2.06		2.14		3.45	
	>7.6	22.91	16.91	-12.48; 58.30		11.22		11.68		18.78	
Puszcza Białowieska (520)	0.0-0.6	2.10	0.42	1.22; 2.98	39.35	1.03	19.28	1.07	20.06	1.72	32.26
	0.61-2.5	6.83	1.10	4.53; 9.13		3.35		3.48		5.60	
	2.51-7.6	16.38	3.70	8.63; 24.12		8.02		8.35		13.43	
	>7.6	14.04	3.70	6.29; 21.79		6.88		7.16		11.51	
Puszcza Białowieska (521)	0.0-0.6	1.47	0.19	1.06; 1.87	16.49	0.72	8.09	0.75	8.41	1.20	13.52
	0.61-2.5	4.55	1.33	1.77; 7.33		2.23		2.32		3.73	
	2.51-7.6	6.73	1.59	3.41; 10.05		3.30		3.43		5.51	
	>7.6	3.75	1.89	-0.21; 7.71		1.84		1.91		3.08	

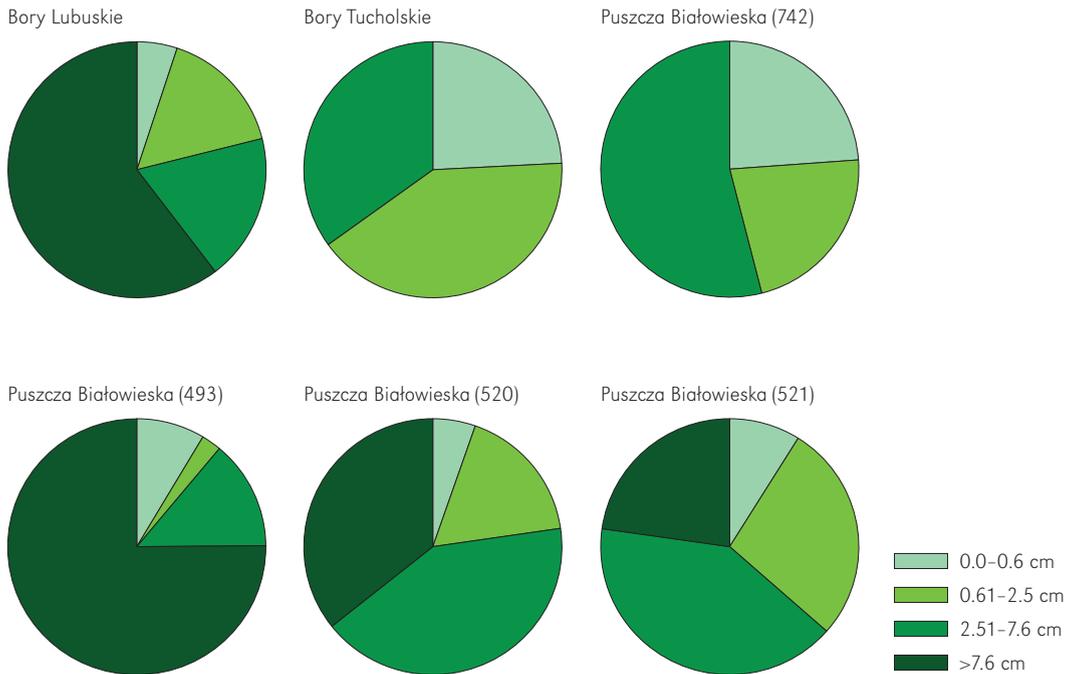


Figure 5. Percentage share of diameter classes in total dead wood volume.

Table 4. Forest floor area occupied by down wood and average piece length with standard deviation by diameter classes (only pieces with diameter >0,6 cm).

Site name	Diameter class (cm)	Average area (m ² /ha)	Standard deviation	Average length (m)	Standard deviation
Bory Lubuskie	0.61-2.5	181.38	54.06	0.14	0.04
	2.51-7.6	85.77	35.02	0.20	0.06
	>7.6	63.84	35.13	0.98	0.36
Bory Tucholskie	0.61-2.5	241.98	42.30	0.39	0.06
	2.51-7.6	61.71	23.17	0.29	0.12
	>7.6	0.00	0.00	0.00	0.00
Puszcza Białowieska (742)	0.61-2.5	145.19	30.67	0.16	0.04
	2.51-7.6	95.45	29.82	0.65	0.26
	>7.6	0.00	0.00	0.00	0.00
Puszcza Białowieska (493)	0.61-2.5	60.17	20.13	0.23	0.08
	2.51-7.6	129.70	48.18	0.58	0.27
	>7.6	106.89	50.52	1.46	0.64
Puszcza Białowieska (520)	0.61-2.5	557.21	86.47	0.48	0.08
	2.51-7.6	454.23	84.04	3.05	0.54
	>7.6	181.79	44.33	3.47	0.64
Puszcza Białowieska (521)	0.61-2.5	373.22	98.04	0.25	0.04
	2.51-7.6	208.94	42.43	0.81	0.23
	>7.6	43.88	18.97	0.38	0.17

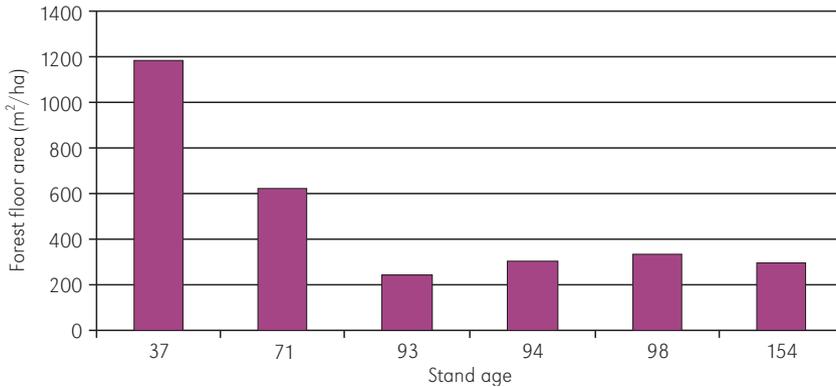


Figure 6. Total forest floor area occupied by down wood (Y axis) depending on stand age (X axis).

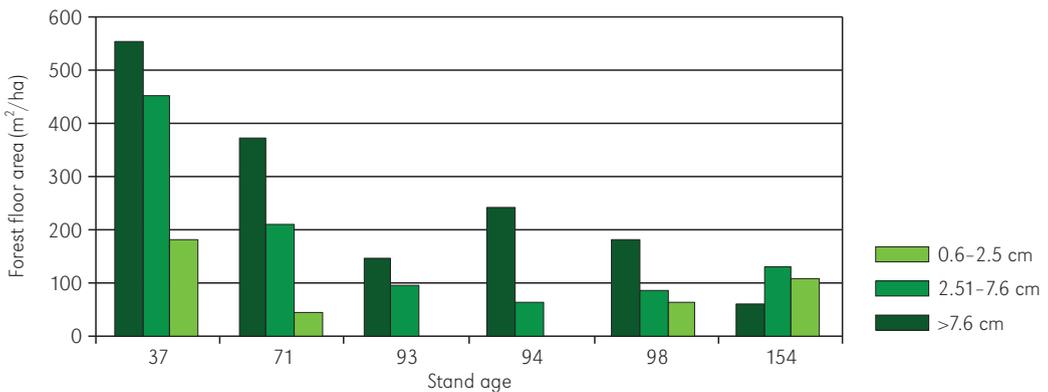


Figure 7. Forest floor area occupied by down wood (Y axis) depending on stand age (X axis) and diameter class.

DDW volume there ranged from 5.11 m³/ha to 30.48 m³/ha (Tab. 3, 4; Fig. 6). In this case, FWD (0.6-2.5 cm) was the dominant diameter class, with negligible contributions of the thickest fractions. Plot 493 in Puszcza Białowieska, where these proportions were reversed, was an exception (Fig. 7).

The mean length of FWD (0.6-2.5 cm) did not exceed 0.5 m, while thicker fragments had a mean length not greater than 1 m (with the exception of Plots 493 and 520 in Puszcza Białowieska) (Tab. 4).

Discussion

The comparison of DDW volume in different aged forest stands at the six experimental plots suggests a correlation represented graphically as a hyperbole with a minimum in the age range of 80-100 years (Fig. 8). The course of the cumulative curve resembles that of the regression curve for CWD (>7.6 cm) - clearly indicating that CWD is responsible for the observed correlation.

The correlation between stand age and the amount of FWD was much weaker, decreasing considerably as the diameter of the classes decreased. The literature hardly supplies comparative data as such detailed investigations of the smaller fractions of woody detritus are very rarely undertaken abroad (e.g. Page-Dumroese & Jurgensen 2006; Woodall & Monleon 2010), and no such studies have been carried out in Poland. Ignoring the smaller fractions is, however, not advisable. This is particularly true in managed forests, where CWD is not abundant and FWD plays an important role in the circulation of elements and carbon accumulation in the litter. Such material also increases the species diversity of mosses (Kruys & Jonsson 1999; Ódor & Standovár 2001), and even has a beneficial effect on the abundance of some small mammal populations (Ecke et al. 2001).

The above data (particularly those concerning CWD) are consistent with many other observations

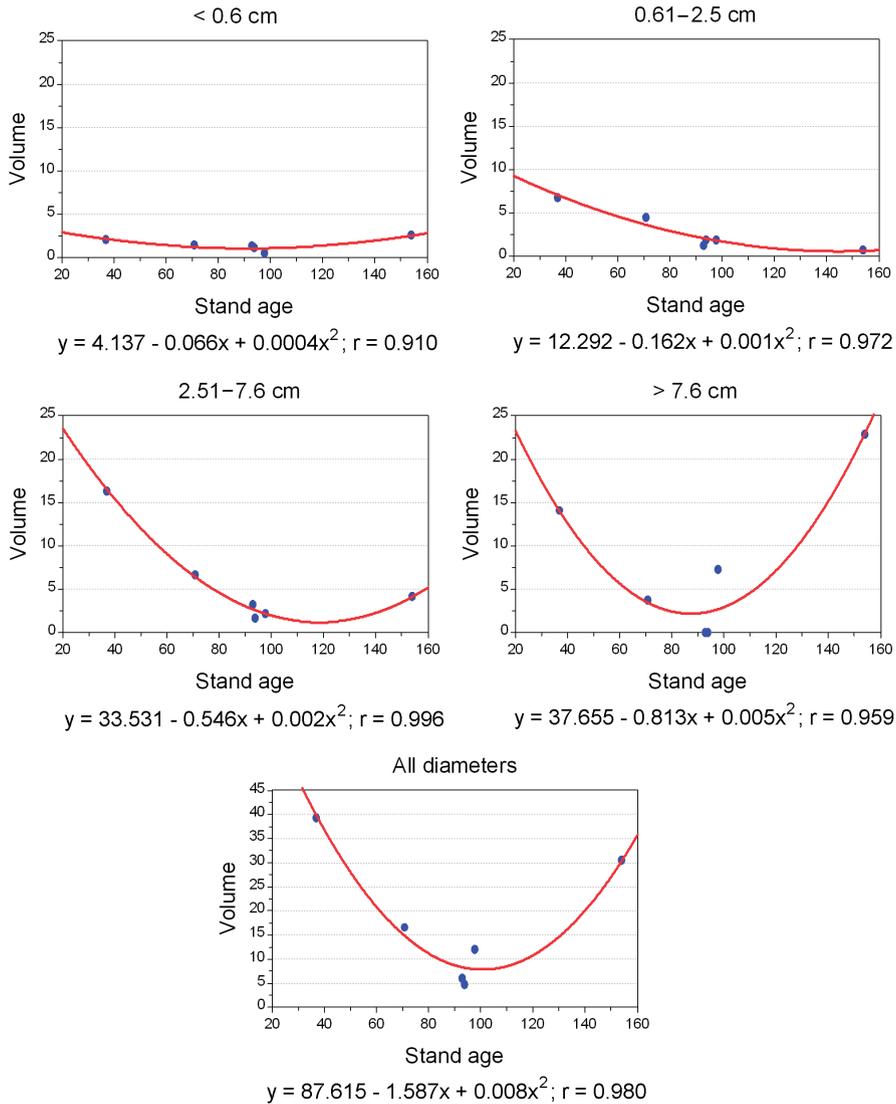


Figure 8. Regression curves for dead wood volume (m³/ha, Y axis) depending on stand age (X axis) and diameter classes.

from both managed and natural forests (Spies & Cline 1988; McCarthy & Bailey 1994; Harmon & Sexton 1996; Lofroth 1998; Spetich et al. 1999) (Tab. 5). This may mean that irrespective of the type and intensity of forest management, general trends of change in the amount of DDW as stands grow older, remain the same and follow the course and succession of natural processes. A confirmation of this hypothesis during further studies, may have tremendous importance for the development of new principles in DDW management.

The present results also indicate that stand age influences not only the available volume of DDW, but also the size of pieces and area shared. It appears that a crucial role here is played by the developmental phases a stand goes through during its life cycle.

In the young growth phase (15-40 years), there is marked shedding of branches from trunks and intense dieback of weaker trees. An additional source of DDW in managed forests is what is left after late cutting and early thinning. This course of natural processes and forest management

Table 5. Stock of dead wood in different forest ecosystems – examples.

Dominant tree species/stand	Age	Volume (m ³ /ha)	Region	Country	Literature
<i>Pseudotsuga, Tsuga</i>	515	1,421	Oregon	USA	Agee & Huff (1987)
Riparian <i>S. giganteum</i>	old-growth	1,104.5	California	USA	Harmon et al. (1987)
<i>Pseudotsuga, Tsuga</i>	19	981	Oregon	USA	Agee & Huff (1987)
<i>Pseudotsuga, Tsuga</i>	3	673	Oregon	USA	Agee & Huff (1987)
<i>Tsuga heterophylla</i>	mature	390	x	Canada	Lofroth (1998)
<i>Pseudotsuga, Tsuga</i>	110	389	Oregon	USA	Agee & Huff (1987)
<i>Sequoiadendron giganteum</i>	old-growth	340	California	USA	Harmon et al. (1987)
<i>Pinus jeffreyi</i>	old-growth	340	California	USA	Harmon et al. (1987)
<i>Pseudotsuga menziesii</i>	404	313	Washington	USA	Spies et al. (1988)
<i>Pinus</i>	mature	268.4	x	Canada	Lofroth (1998)
<i>Pseudotsuga menziesii</i>	65	248	Oregon	USA	Spies et al. (1988)
Riparian <i>P. lambertiana, Abies concolor</i>	old-growth	242.9	California	USA	Harmon et al. (1987)
<i>Abies concolor, Abies magnifica</i>	old-growth	151	California	USA	Harmon et al. (1987)
<i>Pseudotsuga menziesii</i>	121	148	Washington	USA	Spies et al. (1988)
<i>Quercus sessilis</i>	200	132	Tennessee	USA	Harmon et al. (1986)
<i>Picea, Abies</i>	129-198	111	x	Finland	Siitonen et al. (2000)
mixed with oak	<5	102	North Carolina	USA	McMinn & Hardt (1996)
mixed with oak	>120	102	North Carolina	USA	McMinn & Hardt (1996)
mixed with oak	200	94	Tennessee	USA	Harmon et al. (1986)
<i>Lilodendron tulipifera</i>	30	91.5	North Carolina	USA	McMinn & Hardt (1996)
<i>Acer saccharum</i>	200	86.2	North Carolina	USA	McMinn & Hardt (1996)
mixed with oak	70	83.3	North Carolina	USA	McMinn & Hardt (1996)
<i>Fagus, Betula</i>	200	82	Tennessee	USA	Harmon et al. (1986)
<i>Pinus strobus, Quercus alba</i>	200	65.6	South Carolina	USA	McMinn & Hardt (1996)
mixed with oak	5-39	63	North Carolina	USA	McMinn & Hardt (1996)
<i>Picea</i>	mature	60	x	Canada	Lofroth (1998)
<i>Picea, Abies</i>	x	60	Tatras	Poland	Zielonka & Niklasson (2001)
<i>Liliodendron tulipifera</i>	40	51	Tennessee	USA	Harmon et al. (1986)
<i>Pinus sylvestris</i>	71	39.4	Puszcza Białowieska (521)	Poland	Wolski (2003)
<i>Pinus</i>	mature	36.2	x	Canada	Lofroth (1998)
<i>Picea, Abies</i>	140	36	Leningrad oblast	Russia	Tarasov et al. (2000)
<i>Picea, Abies</i>	180	33	Leningrad oblast	Russia	Tarasov et al. (2000)
<i>Pinus sylvestris</i>	154	30.5	Puszcza Białowieska (493)	Poland	Wolski (2003)
<i>Pinus</i>	50	30	Tennessee	USA	Harmon et al. (1986)
<i>Liliodendron tulipifera</i>	30	22.4	North Carolina	USA	McMinn & Hardt (1996)
<i>Picea, Abies</i>	124-145	22	x	Finland	Siitonen et al. (2000)
<i>Picea, Abies</i>	100	18	Leningrad oblast	Russia	Tarasov et al. (2000)
<i>Pinus sylvestris</i>	27	16.5	Puszcza Białowieska (520)	Poland	Wolski (2003)
<i>Picea, Abies</i>	95-118	14	x	Finland	Siitonen et al. (2000)
<i>Pinus sylvestris</i>	98	12.1	Bory Lubuskie	Poland	Wolski (2003)
<i>Picea, Abies</i>	40	12	Leningrad oblast	Russia	Tarasov et al. (2000)
<i>Pinus sylvestris</i>	93	6	Puszcza Białowieska (742)	Poland	Wolski (2003)
<i>Pinus sylvestris</i>	94	5.1	Bory Tucholskie	Poland	Wolski (2003)

accounts for a very high abundance of DDW pieces of different diameters. These pieces occupy a large proportion of the forest floor (especially smaller, finer pieces) and result in a very high volume of DDW (Puszcza Białowieska 520, 521).

In a maturing stand, tree dieback is very slow and the process of natural shedding of branches dwindles out. The DDW accumulated during the young growth phase is completely or markedly decomposed. Late thinning additionally removes poorly viable trees that register low growth, i.e. potential future DDW. In effect, the forest floor in a mature stand has no CWD, very little “thicker” fractions of FWD (2.5-7.6 cm), and not many of the thinnest twigs. The total DDW volume reaches a minimum there (Puszcza Białowieska 742, Bory Tucholskie).

In the stand ageing phase, some trees reach a natural end of their life. The proportion of CWD increases abruptly. There is also a noticeable, though not so marked, rise in the proportion of FWD which is mainly the branches of dying trees. With such proportions, the percentage of the forest floor occupied by DDW hardly changes, the number of pieces (especially of coarser FWD and CWD) may increase insignificantly, and the total volume of DDW increases substantially (Bory Lubuskie, Puszcza Białowieska 493).

This model, consistent with the course of natural processes and silvicultural practices, largely explains the findings of this study. It is also consistent with other known conceptions of three-stage forest development (Spetich et al. 1999).

Suggestions for down dead wood management in managed forests – a review of the implementation after 10 years

Over the last 10 years, the approach to DDW on the forest floor has undoubtedly changed considerably in Poland. Many scientists, including some foresters, now admit that secondary pest activity or fire hazards associated with DDW do not pose such a big threat for the sanitary condition of forest stands as was believed for decades. A large proportion of society no longer equates a nice-looking forest with a clean forest.

These changes have been brought about by intensive efforts to spread the information about DDW. Training-workshops for foresters in national

parks¹⁰ were made available as well as elective courses at universities (e.g. at the Forest Faculty of Warsaw Agricultural University). Information was displayed in reserves and along nature paths. Information was also published by national parks in promotional materials and displayed on their websites (e.g. http://www.swietokrzyskipn.org.pl/przyroda/martwe_drewno) as well as in the nature sections of regional WWW portals (e.g. <http://www.poznajtaty.pl>).

Are these efforts to raise awareness parallel with more profound changes leading to practical action? To what extent are the dilemmas we faced 10 years ago still relevant? Have our proposals and suggestions for leaving DDW in forests (Solon & Wolski 2002, 2005), been successfully implemented?

Our initial intention was to modify the existing principles of forest management (both at the level of general assumptions and that of specific practices) with little accompanying change in the organising principles of forest economy. General modifications were meant to promote DDW as a dynamic component related to the structural characteristics of the forest stand that appears and disappears in an irregular fashion in time and space. The management of DDW was to be seen as an element of a new and internally consistent silviculture (Bobiec 2002).

We also presented detailed suggestions relating to direct silvicultural practices in forests (Solon & Wolski 2002). These concerned:

- ensuring the continual presence of DDW between forest generations by the simple measure of leaving solitary standing trees and coarse downed material in clear felling sites,
- leaving dead standing trees and downed wood of different sizes and in different stages of decomposition, or even locally accelerating the dying out of selected trees (e.g. weak and harmful individuals) by girdling, creating artificial hollows, grafting fungi or pollarding,
- discontinuing the practices of disturbing, storing and cutting material to be set aside and left in the forest, and halting the practice of destroying (fragmenting) trees already downed

¹⁰ Training workshops are offered, among others, under the initiative “Building a common information exchange platform and a system of professional training in national parks”, co-funded by the European Union as part of the Programme “Infrastructure and the Environment” and implemented by the National Foundation for Environmental Protection.

(especially at sites where heavy machinery is at work, such as felling sites or near trackways).

Have these recommendations been included in the latest documents related to forest management? The problem of dead trees has been addressed to the greatest extent in the "Forest Protection Instructions" (CILP 2012a), where one of the most important principles for the protection of forest ecosystems is "to leave in a managed forest, a particular mass of dead trees and their fragments until natural decomposition". This necromass is defined as "standing or downed dead trees and silvicultural exploitation residue and tops abandoned by pests foraging under insect-infested bark and feeding in the wood". The document also contains the provision that "from the viewpoint of forest protection and promoting forest resistance, silvicultural practices should specifically aim to: [...] ensure the continuity of all development phases of trees and tree stands, and dead trees in various stages of decomposition". "The principles of silviculture" (CILP 2012c) include the statement that "useful trees are [...] trees with hollows and, if deemed advisable, also dead trees". "Instructions for forest development" (CILP 2012b) contains guidelines for measuring DDW in selected representative sampling plots. Such stipulations raise our spirits by the very fact that they exist. The vague wording, however, do not give us reason to be totally optimistic, especially when the phrase is included: "the amount of dead wood left in the forest shall be determined by the forest inspector". The latest edition of the Forest Stewardship Council (FSC) standards and certification principles (Forest Stewardship Council 2012), has included some statements that naturalists can welcome regarding DDW management. At the same time, the Council's suggested ways for accelerating the dying process of selected trees are still regarded as too controversial, even though such practices (*management for decadence*) are not unusual abroad (Gutowski et al. 2004).

Another issue we focused on 10 years ago, was the necessity of arranging DDW volume measurements according to a consistent method in a variety of forest types located in various regions of Poland. Our intention was that the measurements would be carried out both in natural forests, and in managed forests which have a well-documented management history (cf. Heath & Chojnacki 2001). At present, individual inventories and/or research work are conducted according to grossly

diversified measurement methodology (e.g. Bo-biec & Stachura-Skierczyńska 2007; Czerepko 2008; Ryś 2008). While unitary results do provide valuable data on the diversification of DDW resources in various forest ecosystems, comparisons between them may produce conclusions that are quite at odds with reality (cf. Dudley & Vallauri 2004). Thus, there is still an urgent call for a consistent method, especially since there have been increasingly intense inventory efforts over the last decade. The need for developing a consistent method should not, however, be construed as a call to use a particular method. What is needed is a set of methods applied consistently all across Poland's forest ecosystems (Woldendorp et al. 2002, 2004).

We also pointed out that the survival of many animal and plant populations is influenced not only by the volume (amount) of DDW, but also by its quality, and particularly by:

- the size of the woody pieces; for instance, moss and lichen diversity depends heavily on the surface area of wood available for colonisation; the highest species diversity can be achieved when DDW of all diameter classes is present in the forest (Kruys & Jonsson 1999),
- degree of decomposition, which is a precondition for the presence of certain species of small insectivorous mammals (Lofroth 1998) that look for food in more highly decomposed pieces and take shelter in less transformed ones (Bunnell et al. 1999).

This qualitative aspect is now receiving attention, with some works actually treating the qualitative aspect at least as important as the quantitative aspect (e.g. Ciach 2011; Hilszczański et al. 2011). Also of relevance is the spatial distribution of DDW. An example would be the storing of DDW in one place which may lead to the extinction of species with limited dispersal abilities. Specific forest management solutions also play a role. For example, the fact that wood remaining after felling is colonised by only 40-50% of the species of fungi that are present on dead logs in non-managed forests, needs to be taken into account (Sippola & Renvall 1999).

However, there is no escaping the subject of quantity. There is not much exaggeration in the statement that, there are as many answers to the "How much?" question as there are research teams, study authors, and study objects. The few examples given below are just a modest

illustration of the sometimes very conflicting views on the issue of quantity of DDW that should be left in a forest, especially a managed forest. Early attempts at estimating the quantities, were undertaken in the states of Oregon and Washington, USA, in the late 1970's. These attempts were related to the determination of the living needs of populations of individual bird species, especially wood-peckers (Maser et al. 1979; Thomas et al. 1979). Those solutions can hardly be regarded as universal since only standing trees with hollows were analysed and the results pertained to a specific animal group with rather peculiar needs. The planning of nature conservation should be based on sets of species (cf. Ciach 2011). However, any study where zoological indicators are applied to estimate the minimum amount of DDW required, should account for "extinction thresholds" of individual species. This is especially true of saproxylic and umbrella organisms.

Another solution is based on comparing existing DDW resources in various types of natural and managed forests. The authors of the *Blue River Residue Guideline* (1986), used in Willamette National Forest in Oregon, USA, recommend leaving 10-15 logs of dead wood per acre of forest if the cross-section diameter is in the range 40-107 cm, 8 logs for the diameter range 107-152 cm (with 2-7 additional smaller logs) or 5 thicker ones (with 5-10 smaller ones) of a minimum length of 2.4-9.1 m. The guideline also claims that no trees in the 3rd, 4th or 5th stage of decomposition should be removed from the forest (Harvey et al. 1976, 1978, 1979, 1981; Caza 1993).

A very formal approach has been proposed by Ducey and Gove (2000), who presented a logarithmic correlation between the number and length of dead wood pieces per unit of area vs. diameter class size. Yet another solution for managed forests, is to leave clumps of trees that will not be disturbed by humans (Franklin et al. 1981). For instance, according to an American study, there should be 0.1 ha of unmanaged forest stand for every 2 ha of a production forest (Hilszczański 1997).

The World Wide Fund for Nature (WWF) suggests leaving approximately 20-30 m³/ha of dead wood in forests in our climatic zone (Dudley & Val-lauri 2004). Similar figures are suggested in the *BioSoil* project, which states that conditions for preserving the biodiversity of saproxylic organisms are good or excellent for wood necromass volumes of 20-30 m³/ha or over 30 m³/ha, respectively (Czerepko 2008). In turn, Gutowski and his team (2004) stated that DDW should constitute 15-20% of the stand volume in protected forests where valuable specimens of nature are present (Forest Promotional Complexes undoubtedly belong to this group). They state that the "ratio" per hectare should include at least 10 thick rotting whole logs or standing dead trees more than 40 cm in diameter and as many trees with hollows as possible.

In conclusion, the postulates we made 10 years ago must be remembered. Our recommendations have been quoted many times by other researchers since then. We stipulated that decisions regarding the quality and quantity of wood necromass left in a forest must not be arbitrary but should be based on detailed investigations. It is only by determining the actual resource of DDW, and analysing its volume and degree of decomposition in various types of forest stands of different age and different physico-geographical conditions that principles of the management of DDW can be finally formulated. The plan should not be in the form of local guidelines, but in the form of comprehensive strategies¹¹ involving forestry as well as ecological and economic viewpoints. We do not want to have to raise the question: will we have to wait another decade?

Editors' note:

Unless otherwise stated, the sources of tables and figures are the author(s), on the basis of their own research.

¹¹ Examples of such comprehensive strategies targeting both managed and natural forests include *A Short-term Strategy for coarse woody debris management in British Columbia's Forests* (BC Ministry of Forests 2000) or *Maintaining coarse woody debris in post-harvest settings* (Davis et al. 2000).

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GEOGRAPHIA POLONICA

CONTENTS

BJÖRN BERG

Scots pine needle litter – can it offer a mechanism for carbon sequestration?
Presentation of a theory

ANDRZEJ BYTNEROWICZ • WITOLD FRĄCZEK

Large-scale monitoring of air pollution in remote and ecologically important
areas

RYSZARD LASKOWSKI

What determines forest litter decomposition? Global trends and local
variance

KAZIMIERZ RYKOWSKI

The basics of sustainable forest management in Forest Promotional
Complexes

KRZYSZTOF BŁAŻEJCZYK • ANNA BŁAŻEJCZYK

Changes in UV radiation intensity and their possible impact
on skin cancer in Poland

EWA ROO-ZIELIŃSKA • BOŻENNA GRABIŃSKA

Ecosystem services – classification and different approaches at various
levels of biosphere organisation – a literature review

JERZY SOLON • MAREK DEGÓRSKI

Geographical patterns of selected features of the soil and herb layer
in central and north European scots pine forests

JACEK WOLSKI

Down dead wood in a forest – still an obstacle
to forest management or already an ecological issue?