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REVIEW PAPER

Innovative methods of non-destructive evaluation of log quality

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Abstract

For the sustainability of an important renewable resource, such as wood, it is important to significantly increase the efficiency of its processing. A large part of this raw material ends up in the wood processing industry, where it is used for the production of pulp, paper, construction and furniture timber, floors and others. Therefore, it is very important to gain the knowledge needed for optimal valuation of raw wood material, through quality detection and classification into quality classes. There are many defectoscopic methods working on different physical principles. The most familiar of these methods are semi-destructive and non-destructive, as they do not cause damage to the tree or wood during assessment. The aim of this article is to describe, assess and compare known semi-destructive and non-destructive methods for the assessment of wood properties. This article describes basic visual inspection, basic semi-destructive methods (Pilodyn, Resistograph) and advanced semi-destructive methods (SilviScan®, DiscBot®) as well. Non-destructive methods use mostly acoustic wave motion (acoustic, ultrasonic), high-frequency waves (using georadar, microwave) and methods based on visual evaluation (image, laser). At last, there are X–ray methods with the latest technology using three-dimensional (3D) computed tomography (CT). The implementation of modern non-destructive methods is of great importance for the application of principles of Industry 4.0, where these methods provide collecting of data on the material properties, in its entire production flow of log processing.

Key words: X–ray method; acoustic methods; georadar methods; laser methods; industry 4.0, CT scanner

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1. Introduction

Today, under growing pressure from society, ecological standards and the developing industry in our country and in the world, there is an increasing emphasis on assessing the quality and origin of wood raw material. For these reasons, the European Union has developed several instruments aimed at the ecology, regulation and legalisation of harvesting. In 2003, "Forest Law Enforcement, Governance and Trade" (FLEGT) was created to prevent illegal timber trade and encourage investment in legal harvesting in developing countries. "Reducing emissions from deforestation and degradation" (REDD) offers a new method how to reduce CO_2 emissions by paying for actions, to prevent deforestation or forest degradation. Rising social and ecological standards have given rise to FSC (Forest Stewardship Council) certification, which is a trusted system for forest certification and certification of the processing (consumer) chain of wood processing worldwide.

Evaluation of the quality of wood raw material and its sorting has a significant effect on maximising yield. Financial, quantitative, but also ecological reasons are important for the increasing yield. Globally, there is a great shift in the intensity of forest management and log processing, which requires significantly faster and more accurate evaluation of wood properties. Unlike concrete, bricks, steel, aluminium and most other construction materials, wood has highly complex, anisotropic and variable internal structure. For the correct use of woodand products based on it (plywood, KVH prisms, timber, OSB boards, etc.), it is necessary to evaluate the properties of this material.

There are a number of methods for evaluating wood. They can be divided, according to the degree of destruction of the evaluated material, into: *1. destructive, 2. non-destructive, 3. semi-destructive methods*. Non-destructive and semi-destructive methods are more important in the evaluation of wood. Non-destructive evaluation is the identification of the physical and mechanical properties of a material without altering its end use and, using the identified properties, decides on its appropriate applications (Ross et al. 1998). In contrast, semi-destructive techniques for evaluating wood properties are defined as test procedures that are non-destructive in relation to the structural element but destructive in relation to

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the extracted sample (Kasal et al. 2013). In the forestry context, non-destructive evaluation of wood (NDE) is considered attractive. Authors Schimleck, et al. (2019) described the main reasons why the NDE has grown rapidly over the last 20–25 years: Protection of investment in wood raw material; potential to reduce wood processing costs; easier to use for field measurements; fast real-time data collection; the ability to identify the most suitable measurement application and reduce the variability of product classes.

This article focuses on the description and mutual comparison of non-destructive and semi-destructive methods of wood evaluation, working on various physical principles, described from basic methods to today's most modern. The methods will be examined in relation to their use in forestry and the wood processing industry, as these sectors are significantly interrelated.

2. Evaluation methods for wood

The main goal of wood evaluation is to assess qualitative properties, sometimes supplemented by quantitative ones. For qualitative evaluation, it is necessary to determine the mechanical and physical properties of wood. Non-destructive methods determine, for example, mechanical properties (moduli of elasticity, impact strength etc.) and physical (moisture, density, acoustic properties, visual properties etc.). Another part of the qualitative evaluation is the determination of wood defects (knots, cracks, rot, irregularity of the wood structure, foreign objects, traces of biological damage, etc.). The identified properties significantly affect the subsequent sorting of wood products, yield and thus the financial appreciation of wood.

The basic, still widely used evaluation is **visual inspection**. The method is very fast, with lower costs. It allows to obtain basic information in situ about the assessed tree or log. Visual inspection allows only the detection of external, visible defects and mechanical damage to the wood. Another disadvantage is the higher demand on the expertise of the assessor, which can increase the overall cost. Visual inspection is also the basis for in situ visual classification according to the quality classes of logs and classification of construction timber into strength classes. Visual evaluation is strongly represented in supplier-customer relations in log trading. Here, the log is most often sorted according to the standards STN EN 1316–1 – 3 for broadleaf raw material and STN EN 1927–1 – 3 for coniferous raw material. These standards determine the evaluation parameters of raw logs for classification into four classes (A, B, C, D). Results of the visual inspection form the basis from which subsequent non-destructive testing (NDT) can be planned (Piaza et al. 2008). To evaluate the quality of wood, a large number of devices have been developed that can assess the properties of timber logs, veneers and other wood products.

2.1. Semi-destructive methods

Semi-destructive methods damage the material only partially without affecting its further use. They are used mainly to evaluate the properties of wood, logs, or historic roof constructions. A new approach to the historic roof structures properties assessment is described in the publication (Kloiber et al. 2015). The authors describe recently developed assessment methods such as tensile strength of small samples, tensile Young's modulus of mesospecimens, compression strength of cores, compression strength in a drilled hole, mechanical resistance to pin pushing, Young's modulus derived by measuring the hardness and shear strength of screw withdrawals. They do not belong to the industrially used methods, they are used mainly for scientific work. They are described here for their use in evaluating the quality of trees, which helps in the classification of wood according to quality, already in the first phase (standing tree).

Pilodyn is a portable tool for evaluating the density of trees or wooden constructions. The tool was originally developed in Switzerland to obtain quantitative data on the degree of soft rot in wooden poles. The tip penetrates the surface of the material, measuring the depth of penetration (Cown 1978). The penetration depth of the pin negatively correlates with the density of the wood. Three different rods (diameter 2.0, 2.5 and 3.0 mm) enable to adapt the use of Pilodyn to the density of tested wood (Gao et al. 2017). In practice, the accuracy of Pilodyn is somewhat limited, so it is mainly used to estimate average values (Cown 1978). It is one of the least invasive sampling techniques, but unfortunately it cannot penetrate the middle layers of the trunk. It is also assumed that tested wood is above the fiber saturation point (FSP), as the penetration of the tip decreases with decreasing moisture content below the FSP (Llana et al. 2018).

The resistograph began to develop in the early 1990s (Rinn et al. 1996). It was utilised for improving the identification of rot in trees and poles. The tool drives a special drill (needle) with a diameter of 3 mm through a tree at a given feed speed and rotation speed (rpm) and measures the resistance to rotation (torque). The trace represents the resistance profile every 0.1 mm and the radial change in wood density (Rinn et al. 1996; Downes & Lausberg 2016). Gao et al. (2017) concluded that compared to other semi-destructive techniques, Resistograph was a cheaper and faster method for collecting wood density data. The key features of this tool are its low cost for field use, digital data collection and relatively high-resolution data (Schimleck et al. 2019). Research by Kloppenburg, (2018) focused on the possibility of using the Resistograph to accurately assess the wood density of tropical hardwoods. The tool has proven to be suitable, but the sharpness of the tool has a significant effect on accuracy.

Specific devices are **SilviScan®** and **DiscBot®**. Both of these devices are developed more for laboratory evaluation of wood (logs, timber). They are more invasive, as it is necessary to take a sample (a prism, a disc) for evaluation. The first of these, the **SilviScan®**, is a special laboratory device designed to measure wood quality parameters such as the density and angle of microfibrils (Schimleck et al. 2002). The device was created by Dr. Robert Evans and developed with his CSIRO team as early as 1992. So far, 3 versions of this device have been created. The main components of SilviScan are (Schimleck et al. 2019):

– Optical cell scanner (radial and tangential tracheid and fiber diameters, vessel size and their position, a boundary and orientation of annual rings);
– X–ray densitometer (conditioned density profile, fiber tilt, annual ring transition);
– X–ray diffractometer (microfibril angle, tracheid and fiber 3D orientation, cellulose crystallisation).

A stiffness estimate generated by SilviScan® is based on the diffractometric and densitometric properties of wood, calibrated by the acoustic resonance technique (Ilic 2001). The device has been tested in many studies and has proven to be very accurate (Buksnowitz et al. 2008; Schimleck et al. 2002).

Another special device is the **DiscBot**, developed by the New Zealand company SCION. The device utilises scanning technologies, which can determine a large number of wood properties affecting the resulting quality of timber and other final products. The scanner uses automatic motion of wooden discs under various sensors that capture information on wood density, microfibril angle and chemical composition. The first sensor is a camcorder for capturing a high-quality colour image (in an RGB spectrum), which allows the identification of wood defects such as knots, resin pockets and compression wood. A spectrograph fitted with an infrared (NIR) camcorder (900–1700 nm) applied in several studies (Jones et al. 2006; Thumm et al. 2010) is used to determine the chemical composition and properties of lignin and cellulose. The wood density is measured using X–rays. The strength of wood is evaluated using an ultrasonic device when the wave passes through the wood along the fibers.

2.2. Non-destructive methods

Non-destructive evaluation is the identification of the physical and mechanical properties of a material without altering its end use and, using the identified properties, decides on its appropriate applications (Ross et al. 1998). Previously, non-destructive methods were applied to evaluate very valuable (e.g. exotic) wood species. Currently, these methods are increasingly preferred, because they do not degrade the raw material (wood), they are accurate and are fast. This is applied mainly in automated modern sawmills, where the identified parameters help to better evaluate the processed raw material. The most commonly used physical principles in non-destructive evaluation are: acoustic, ultrasonic, microwave, imaging, laser and X–ray.

2.2.1 Acoustic and ultrasonic methods

Acoustic methods of wood evaluation are among the oldest methods of evaluating the properties of wood. As defined in (Lipta el al. 1972), acoustic velocity is in a form of transitional elastic waves generated by the rapid release of energy in a material. Thus, the source is an acoustic impulse, such as a hammer impact, or an excited acoustic signal (sound). Therefore, scanning the speed of acoustic waves in wood is most often used for evaluation. Another non-destructive acoustic method is ultrasonic measurement. Ultrasound is a mechanical wave with a frequency generally greater than 20 kHz (Wang et al. 2002). The diagnostic tools operate with frequencies in the range from 20 kHz to 500 kHz. During the measurement, ultrasonic waves to the object are generated and subsequently the transmitted waves are measured to identify the transmission properties of wood (Österberg 2009). To increase the contact of ultrasonic receivers and transmitters, it has proven appropriate to immerse the examined wood into a water bath (McDonald 1978; Han & Birkeland 1992).

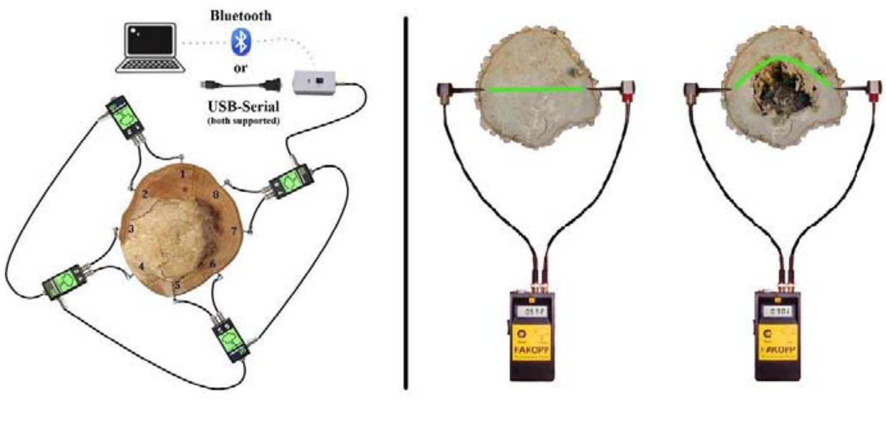

Fig. 1. Principle of measurement by acoustic tools: FAKOPP, a TreeSonic™ model and Microsecond Timer.

The development of acoustic devices for the evaluation of standing trees opened the way for assessing the properties of tree wood before their harvesting. This facilitates the management, planning of harvest and wood processing in a way that maximizes the value extracted from the source (Riggio et al. 2008; Carter 2017). In the last few decades, acoustic technologies have become well-established devices for material evaluation in the wood processing industry. They have become a widely accepted tool for quality control and product classification (Wang et al. 2004), but also for breeding research, where they are utilised for evaluation of young trees (Lenz et al. 2013).

Most acoustic devices that evaluate the properties of trees are modelled for radial measurement (perpendicular to the trunk axis). For example, these devices: ArborSonic 3D Acoustic Tomograph, Hitman Resonance Tool, IML Impulse Hammer, and FAKOPP company tools (Microsecond Timer, Resonance Log Grader, ArborElectro Impedance Tomograph) (Fig. 1). In contrast to these tools, the FAKOPP TreeSonic™ is developed for measuring in the longitudinal direction of the trunk (Fig. 2). In acoustic systems, the source of the impulse is most often the hammer impact.

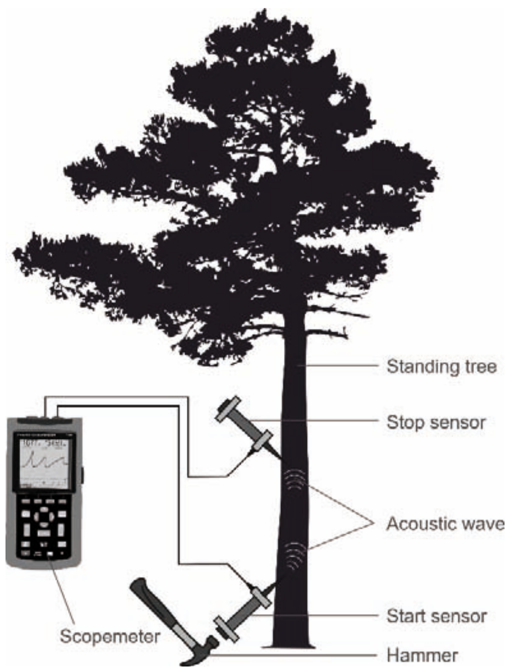

Fig. 2. Acoustic system for measuring standing trees in the longitudinal direction.

Ultrasonic systems evaluate the material mainly perpendicular to the fibers (Fig. 3). The most used ultrasonic devices are FAKOPP IltraSonic Timer, Arborsonic Decay Detector, Sylvatest, V-Meter MK IV System, Proceq Pundit Lab +, Pundit 250 Array and Tico. Most tools evaluate the quality of wood using the determined dynamic modulus of elasticity and density. When evaluating the moduli of elasticity by acoustic tools, different values may occur when repeating the measurement, which causes some inaccuracies in the results, see research: Lindström et al. (2009), Simic et al. (2019).

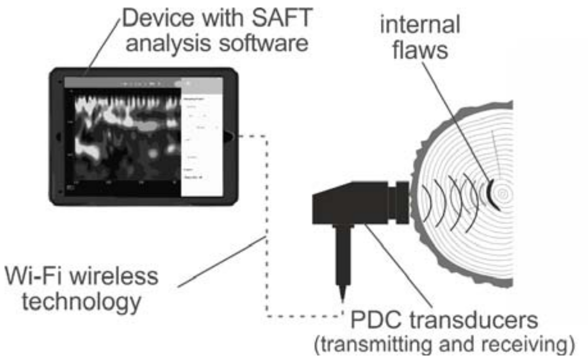

Fig. 3. Illustration of the principle of ultrasonic tomography.

All the mentioned devices are difficult to apply to rapid industrial production. That is why fast acoustic tools are being developed today, measuring at a feed speed of 200 pieces per minute. An example is the Swedish company DYNALYSE, which offers Dynagrade and Precigrade devices for evaluating timber properties. Others are devices for evaluating logs before cutting them. A company based in New Zealand, Fiber-gen, has developed the HITMAN PH330 measuring tools implemented into a forest harvester, the HITMAN LG640 for log processing lines and the HITMAN HM200 manual tool.

2.2.2 Microwave methods

The microwave frequency in the electromagnetic spectrum is between the frequencies of infrared radiation and high-frequency waves, i.e. approximately between the frequencies 1 GHz and 100 GHz, or a wavelength between 1 mm to 1 m (Fuller 1990). However, the boundary between microwaves and infrared or radio waves has not been precisely defined. The microwave scanning method has been under development for several years. The first tools were created to measure moisture and were also applied in industrial production (Tiuri & Heikkilä 1979). At present, research using microwave tomography is known, where the authors describe the detection of internal wood defects with higher accuracy (Pastorino et al. 2015; Boero et al. 2018). Using this technique, it is possible to determine properties such as: density and moisture of wood, deflection and direction of fibers or detection of wood defects as well.

Microwave induced thermo-acoustic tomography (MITAT) combining microwave imaging with ultrasonography. This special technology is mainly used in biomedicine and is still under development and the subject of much research (Ku & Wang 2001; Meaney et al. 2012; Rosenthal et al. 2012; Wang et al. 2013). Research using this technology to determine the properties of wood is known. Authors Zhang et al. (2019) use the thermoacoustic principle combining microwaves and ultrasonic waves for spatial imaging of a hole in a wood sample. The method proves fast and efficient.

2.2.3 Georadar methods (GPR)

This method utilises electromagnetic radiation in the microwave band, high-frequency radio waves (10 MHz – 2.6 GHz) and detects reflected signals from subsurface structures of materials. (July 2008). This technology is most often used for the evaluation of soils, rocks and building elements (concrete, brick walls). However, many studies have pointed to the possibility of using this ground-penetrating technology to evaluate internal wood defects (Nicotti et al. 2003; Muller 2003; Hislop et al. 2009), where microwave radiation with a frequency of 1.5 – 2.5 GHz is recommended. For the evaluation of wood, mainly devices for construction industry are used. Pirouz et al. (2015) in their research compares image, laser, X–ray scanning and technologies using GPR. He uses a device by a Sensors & Software company, namely a Pulse EKKO® type intended for the evaluation of internal rot.

Further research uses similar devices by a GSSI company, namely SIR 3000, SIR 4000 (Senalik et al. 2016). The only device designed directly for the evaluation of wood, or on trees, is TRU™ (Tree Radar Unit) by the American company TreeRadar™ (Wen et al. 2016).

The study (Halabe et al. 2009) showed that GPR can be used to accurately identify internal defects such as knots, cracks, and metal nails that are not commonly visible. Scanning speed, good repeatability and the ability to detect wood moisture are the advantages of this technology. The disadvantage is the limited ability to detect small defects and the complexity of data processing as algorithms for evaluation are still under development. The technology is proving very promising for use in the sawmill indust.

2.2.4 Image and laser methods

The ever-increasing capacities of sawmills and the speed of log processing are forcing wood processors to introduce efficient and fast methods of material evaluation. Various machine vision systems (machine vision) in frequent combination with laser, acoustic and other systems have proven to be suitable solutions. Today, these systems are among the most widely used in modern industrial production, also in the wood processing industry. Computer vision, which deals with the acquisition, processing, analysis and understanding of digital images most often obtained from cameras, camcorders, 3D scanners and other scanning devices, is considered the basis of this method. Its task is to develop theoretical and algorithmic bases for achieving automatic visual understanding (Sonka et al. 2014). Image technology has also become a part of most of these non-destructive scanning methods.

Many authors deal with evaluation methods by means of image technology that utilises analysis of shadows, shades of grey or colour spectrum (e.g. RGB) obtained with the help of camcorders (Hu et al. 2004; Sandak & Tanaka 2005; Faria et al. 2008). Most of the systems used in the wood processing industry can be considered as 2D systems. These systems are mainly used for timber evaluation. Today, more and more 3D scanning technologies using lasers are coming to the fore, with their use mainly for scanning logs in sawmills. Studies dealing with the scanning of standing trees using LiDAR scanners to achieve the evaluation of surface defects before their harvesting, is known (Pirouz et al. 2015; Sauter et al. 2017). In spatial (3D) laser scanning, controlled operation of laser beams is combined with a laser rangefinder. Using specialized software, the shape of the surface of objects can be quickly captured.

The laser was first utilised to irradiate samples when measuring wood in the 1980s. The laser and camcorder were first combined to measure the dimensions. Later, dynamic laser dispersion was also used, e.g. to measure grain orientation (Österberg, 2009). Authors Kowal et al. (2012) and Sioma (2015) deal with the use of 3D images in automatic detection and localization of defects on the wood surface using the laser triangulation method. The work of Thomas et al. (2007) is aimed at scanning the surface of hardwood logs to determine their external defects.

There are several variants of a laser scanner, some with multiple laser beams and one camcorder, while other scanners have two camcorders and one laser. For example, following manufacturers offer the laser scanning method: Cognex (a model: 3D-A5000, In-Sight 9000), JoeScan (a model: JS-25-x-SERIES), LMI Technologies (a model: chroma + scan series, Gocator 2100 Series); SICK (a model: TriSpector 100).

2.2.5 X–ray methods

In the second half of the 1980s, X–ray image methods were in the research phase. Methods developed for use in medicine have been transferred to the wood processing industry (Österberg 2009). Efficient commercial X–ray devices for log and timber evaluation are currently available. The device can detect internal defects of wood, hidden foreign objects, measure properties such as wood structure, moisture and density. However, due to its high cost, X–ray computed tomography (CT) is used only in the largest sawmills. Conventional X–ray scanners are usually based on discrete X–ray scanning in 1–4 directions (sometimes 6), where the object or source of X–rays does not rotate (Grundberg & Grönlund 1997). The difficulty is that even an expensive scanner with six

X–ray directions cannot provide an accuracy similar to that obtainable by the CT scanner (Oja 1997). For these reasons, CT X–ray scanners are coming to the fore today.

There are four generations of CT scanner technology that are known. The first and second generation scan in parallel, the third and fourth generation use rotary fan-shaped scanning, where an object or source of an X–ray beam moves. First generation scanners (Fig. 4a) use a single X–ray detector. The X–ray beam passes through the scanned object and measures X–ray intensities through parallel paths in that object (Schmoldt et al. 1998). They are very simple, affordable but slow. The second generation (Fig. 4b) uses a detector system consisting of multiple X–ray detectors for scanning. It's also simpler, faster, but collects unnecessary large amounts of data with frequent noise. The third generation of CT scanners (Fig. 4c) uses an array of detectors with many detectors usually placed in an arc. These devices are more complex for data processing, but are more accurate. For smaller objects, they collect unnecessary amounts of data and are expensive. The fourth generation (Fig. 4d) has a larger number of detectors placed in a circle. Here, an X–ray source revolves around a scanned object, which is placed on a table. It can produce very accurate 3D images. The fourth generation has the same disadvantages as the third generation but owing to the large number of detectors it is more expensive.

et al. 2019). Determining internal properties such as pith, core, knots, cracks and others is another their use (Stängle et al. 2015; Rais et al. 2017). CT wood scanning technology is also used for determining the content and flow of water in wood (Hansson et al. 2017; Longuetaud et al. 2017). A substantial part of the research is devoted to mathematical algorithms for evaluating the acquired images. Images for the above mentioned research are obtained mainly by means of CT scanners intended for medicine, but there are also modern industrial devices intended for the wood processing industry.

The best known manufacturers of medical macro CT scanners are Siemens and GE Healthcare. There are several manufacturers of micro CT scanners on the market, which are designed for smaller objects that they can scan with higher resolution. These are, for example, BRUKER (SkyScan series), ZEISS (Xradia series), Nikon (Model XT H 225). The Belgian Ghent University (models: EMCT, Hector, Herakles, Nanowood) also developed its devices for micro CT scanning. Other device designed mainly for timber evaluation uses X–rays in combination with other methods (laser, image scanning). Well-known manufacturers are: WEINIG Gruppe (Model CombiScan +), Innovativ Vision (Model WoodEye 5), Microtec (Goldeneye series).

There are very few manufacturers of industrial X–ray scanners designed to scan logs. One of the manufacturers

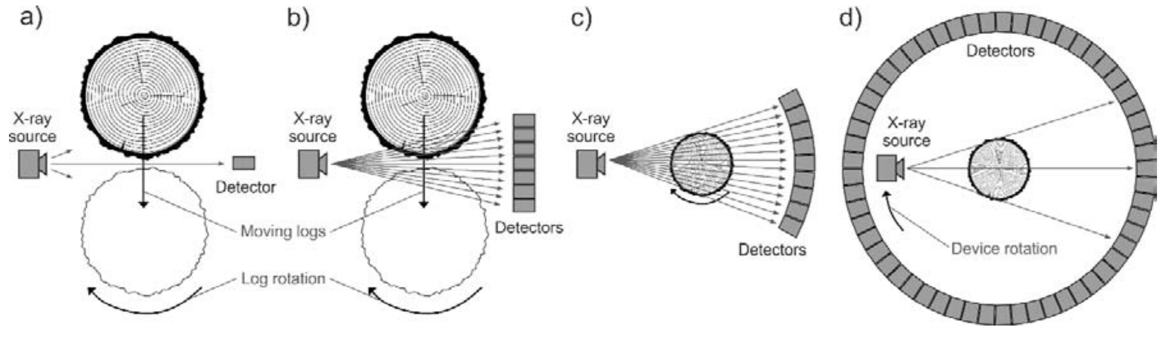

Fig. 4 Generations of CT scanners: a) 1st generation, b) 2nd generation, c) 3rd generation, d) 4th generation.

Most modern CT scanners (4th generation) are equipped with the possibility of spiral CT scanning, which provides almost perfect volumetric reconstruction created from CT images (Beaulieu & Dutilleul 2019). Studies by Schmoldt et al. (1998), Gupta et al. (2004) deal with the design of a tangential CT scanner, where when scanning the detector field is placed parallel to the axis of rotation of the object, parallel to the length of the log. Unlike a typical scanning, where the beam is parallel to the width of the log. This technology is patented (Gupta 1997), but its use in industry is not known.

CT X–ray scanning is becoming more and more affordable, so there is a quantity of research arising for this technology. They are utilised to determine the density of wood and the size of annual increments in coniferous and broadleaf species (Longuetaud et al. 2017; Jacquin

is the German Jörg Elektronik with its JORO-X model with two X–ray sources. The second is a 3D laser scanner with multi-sensor camcorders and an X–ray scanner placed in two positions, produced by the **MICROTEC®** company (**Logeye** series). The Italian company MICROTEC® is the best known and most advanced company dedicated to the field of CT scanners for the wood processing industry. Its **CT log** device (Fig. 5) is the only known device in the world designed for 3D log scanning. The device scans and digitally reconstructs the internal properties of the log what allows to optimise the cutting plan in real time (Microtec 2019). The developed software optimises the bending of the log, determines the best cutting plan to achieve the highest possible quality of the final product. So far, 8 of these devices have been installed in the world (Table 1).

Fig. 5. CT Log scanner. © Microtec (Microtec 2019).

Table 1. Overview of CT Log device installations.

State	Number of CT Logs	Company
Canada	1	Interforest Ltd.
USA	2	Danzer Services, Inc. Idaho Forest Group
Chile	1	Arauco – Horcones
France	2	Piveteaubois Siat Braun
Germany	1	HIT Holzindustrie Torgau
Sweden	1	Norra Timber

3. Applicability and efficiency of methods

Current trends, such as rising costs and limited supplies of quality logs, are causing the increase in efforts to maximise yields in the wood processing industry processing coniferous and hardwood tree species. The production of timber is considerably complicated, due to the high demands on the operation, complexity of the sorting, and the requirements for the accuracy of the sawmill equipment. For these reasons, in today‘s wood processing industry, all process stages are increasingly being modernized and automated. A great benefit for improving yield by automatic cut optimisation is also the introduction of various scanning systems to detect internal wood defects. To a greater extent, these technologies are now used in large sawmills focused on coniferous raw material. However, they are of great importance for cutting more expensive hardwood species.

In terms of applicability, we can divide non-destructive methods into two main categories, i.e. used only for research and applicable for research and industrial practice. Semi-destructive methods are used mainly for research. Most of them are applied in dendrology and forestry for the evaluation of young and older trees. The Pilodin and Resistograph devices are often used in Central Europe. Their utilization is also in wood degradation assessment of roof structures. SilviScan® and DiscBot® devices are very specific not being in Central Europe. Their use in rapid industrial production is very limited. Other methods (microwave methods, methods using georadar) are still under development and further research will be needed for their use in industry, ideally in collaboration with practice. However, there are a number of publications appearing that prove the applicability of these methods.

Described technologies enable different levels of non-destructive evaluation. Österberg (2009) created a table (Table 2), which is suitable for a clear comparison of individual methods. Indicates the level of technology acquisition costs, application level, safety, and suitability for identifying selected features.

It can be deduced from the table that the X–ray method is the most suitable for the evaluation of most parameters. These devices are less wide-spread due to their high prices. In Europe, there are only 4 industrial CT scanners located in France, Sweden and in Germany in terms of the closest distance (see Table 1). Other types of technologies are laser and image ones. Considering that these two technologies are combined in most industrial devices, we can also consider them very suitable for wood evaluation. Laser, image and also acoustic methods are therefore the most used in industrial practice. Their great advantage is affordability as well as advanced

Table 2. Evaluation of individual technologies according to their possibilities.

	Laser	IR	Visible light	Acoustics	Radio frequencies	µ-waves	X-ray
Cost	++	++	+++	++	+	+	---
Applicability	+++	-	+++	+	-	++	+
Safety	-	+++	+++	+++	++	+	--
Performance:							
3D-shape	+++	+++[2]	+++	---	---	-	+++
Rot and decay	---	+	-	++	-	--	+++
Colour defects	---	---	++	---	--	---	---
Compression and tension wood	---	-	+	+	+	+	+++
Cracks and splits	---	+	+	++	-	+	++
Resin pockets	---	-	--	--	-	+	++
Foreign objects	---	-	--	+	++	++	+++
Knots	---	+	+	-	+	++	+++
Wood density	---	-	++	++	+	++	+++
Strength	++	+	++	+	+	+	+++
Annual ring width	---	-	+++	---	---	---	+
Grain orientation	+++[1]	---	+	---	+	++	++
Moisture content	---	++	---	--	+	++	++
Bark content	++[1]	--	+++	---	---	---	+++
Fiber properties	---	---	-	---	---	---	-

[1]when combined with image analysis; [2]is not thermography, i.e. no spectral content is utilised; -- the technology is completely unsuitable for determining the mentioned characteristics; +++ the technology is suitable for determining the mentioned characteristics; ▒ Commercially known techniques.

computer vision technology for image analysis. This results in the possibility of accurate evaluation at high speeds, applicable in fast automated production. Laser, image and acoustic methods, often combined with IR radiation, are used in all large, automated sawmills in Europe. Gradually, however, they started to be used in medium-sized sawmills. These devices are produced e.g. by WEINIG Gruppe, Innovativ Vision, MICROTEC®. MICROTEC® equipment is used in the Czech Republic e.g. by sawmills Mayr-Melnhof Holz Paskov Ltd., Holz Schiller Ltd., Danzer Ltd. In Slovakia there are PRP Ltd. and Rettenmeier Tatra Timber. From these three methods, only the acoustic method has the ability of the evaluation of internal wood structures. Investment in these methods is very important for market competitiveness, especially for large and medium-sized sawmills. Return on investment ranges from 2 to 8 years. The most accurate non-destructive method for evaluating properties is certainly the X–ray method with computed tomography (CT). These devices are slowly applied in modern wood processing plants. The big disadvantage is the high purchase price, which allows the use of this technology mainly in medium and large plants. Gergeľ et al. (2019) confirmed this from the existing research and concluded that there is a demonstrable increase in the profit gained from processed wood from 11.3% to 23.7% for coniferous logs and by 24% for broadleaf logs. In processing broadleaf raw material, the return period for large sawmills is about 3 years and for medium sawmills 8 years. In processing coniferous raw material, the return period is about 4 years for large sawmills and 8 years for medium sawmills.

The Italian **Microrec®** company, which offers technologies using all the mentioned methods (acoustic, image, laser, X–ray), is the important company in the development of these automation technologies. In all technological industries, the Industry 4.0 application comes to the fore, or the modernization and automation of production lines, associated with the need to obtain a large amount of data on material. The Microrec® company has developed the Sawmill 4.0 – Digital Fingerprint system, which applies their non-destructive wood evaluation technologies to achieve the greatest possible automation of coniferous and broadleaf wood cutting. Combination of their devices (CT Log, Logeye, Goldeneye) and the implementation of artificial intelligence allows to create a record for each board that is monitored throughout the process. This makes it possible to qualitatively classify the final products and thus make the most of them.

4. Conclusion

Analysis of existing methods for evaluating the quality of wood properties, using semi-destructive and non-destructive technology. Semi-destructive technologies can be used mainly for scientific activities and for growers. Currently, some non-destructive methods are only applicable to scientific activities and their introduction into industrial practice is the future. The most widely used non-destructive methods in industry are image, laser and acoustic methods. These technologies are now more available and allow very fast evaluation of wood properties. However, the possibilities of these technologies are limited mainly to surface defects, with the exception of acoustic ones. The X–ray method, mainly using computed tomography, is certainly the most accurate method. Most X–ray devices create 2D images of the scanned material. The CT Log by Microrec® company is considered the most advanced device as it enables 3D X–ray scanning of the log in real time. It can thus detect internal defects with high accuracy, and then choose the optimal cutting pattern to achieve the highest quality of the final product (timber).

For modern sawmills of the third millennium, it is necessary to invest in modern non-destructive methods of wood evaluation to increase the yield of a quality final product. These technologies can significantly increase competitiveness. The use of Industry 4.0, or modern automated log cutting lines, is certainly the future in the wood processing industry. Streamlining of production under Industry 4.0 anticipates achieving almost zero production downtime and transparency. This requires the processing of huge amounts of data from a variety of sensors and transducers. To process this data, special systems using machine learning, neural networks and artificial intelligence are applied. The Microrec® company applied this method and developed its own Sawmill 4.0 system – Digital Fingerprint. This technology enables to create a separate record with all the data obtained for each board from scanning the log to the final product. This facilitates a significant increase in the degree of automation on sawmills. These processes are the basis for creating a reliable system that will monitor the flow of wood from its harvest to the final product.

The implementation of these technologies within the European area is very different. Sweden, Finland and, in the area of Central Europe, Germany and Austria have a significant competitive advantage in the utilization of these technologies. These countries are significantly innovating and automating the entire log processing process. Scanning technologies are used only at the two largest sawmills in Slovakia, but they are gradually started to be used by medium-sized log processors. It is strongly recommended to support this trend, e.g. by subsidies, because these technologies mean significant savings and improved quality of wood raw material.

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References

Beaulieu, J., Dutilleul, P., 2019: Applications of computed tomography (CT) scanning technology in forest research: a timely update and review. Canadian Journal of Forest Research, 49:1173–1188.

Boero, F., Fedeli, A., Lanini, M., Maffongelli, M., Monleone, R., Pastorino, M. et al., 2018: Microwave tomography for the inspection of wood materials: Imaging system and experimental results. IEEE Transactions on Microwave Theory and Techniques, 66:3497–3510.

Buksnowitz, C., Müller, U., Evans, R., Teischinger, A., Grabner, M., 2008: The potential of SilviScan's X–ray diffractometry method for the rapid assessment of spiral grain in softwood, evaluated by goniometric measurements. Wood Science and Technology, 42:95–102.

Carter, P., 2017: Acoustic technology – Enhanced tools for research and operations. In: Proceedings of the 20th International Nondestructive Testing and Evaluation of Wood Symposium – 2017, Madison, WIS, USA, p. 12–15.

Cown, D. J., 1978: Comparison of the Pilodyn and torsiometer methods for the rapid assessment of wood density in living trees. New Zealand Journal of Forestry Science, 8:384–391.

Downes, G. M., Lausberg, M., 2016: Evaluation of the RESI software tool for the prediction of HM200 within pine logs sourced from multiple sites across New Zealand and Australia. NZ Solid Wood Innov, 15 p.

Faria, J., Martins, T., Ferreira, M., Santos, C., 2008: A computer vision system for color grading wood boards using fuzzy logic. In: IEEE International Symposium on Industrial Electronics – 2008, Cambridge,p. 1082–1087.

Fuller, A. B., 1990: Microwaves: an introduction to microwave theory and techniques. Pergamon Press, 326 p.

Gao, S., Wang, X., Wiemann, M. C., Brashaw, B. K., Ross, R. J., Wang, L., 2017: A critical analysis of methods for rapid and nondestructive determination of wood density in standing trees. Annals of Forest Science, 74:27.

Gergeľ, T., Bucha, T., Gejdoš, M., Vyhnáliková, Z., 2019: Computed tomography log scanning–high technology for forestry and forest based industry. Central European Forestry Journal, 65:51–59.

Grundberg, S., Grönlund, A., 1997: Simulated grading of logs with an x–ray log scanner-grading accuracy compared with manual grading. Scandinavian Journal of Forest Research, 12:70–76.

Gupta, N. K., Hughes, S. H. C., Isaacson, B., 2004: Tangential CT, a computed tomography method developed for industrial inspection. In: 16th World Conference on Non-Destructive Testing – 2004, Montreal,37:379–384.

Gupta, N. K., 1997: U.S. Patent No. 5,648,996. Washington, DC: U.S. Patent and Trademark Office, 13 p.

Halabe, U. B., Agrawal, S., Gopalakrishnan, B., 2009: Nondestructive evaluation of wooden logs using ground penetrating radar. Nondestructive Testing and Evaluation, 24:329–346.

Han, W., Birkeland, R., 1992: Ultrasonic scanning of logs. Industrial metrology, 2:253–281.

Hansson, L., Couceiro, J., Fjellner, B. A., 2017: Estimation of shrinkage coefficients in radial and tangential directions from CT images. Wood Material Science & Engineering, 12:251–256.

Hislop, G., Hellicar, A. D., Li, L., Greene, K., Lewis, C., Meder, R., 2009: Microwave radar for detection of resin defects in *Pinus elliottii* Engelm var *elliottii*. Holzforschung, 63:571–574.

Hu, C., Tanaka, C., Ohtani, T., 2004: Locating and identifying sound knots and dead knots on sugi by the rule-based color vision system. Journal of Wood Science, 50:115–122.

Ilic, J., 2001: Relationship among the dynamic and static elastic properties of air-dry *Eucalyptus delegatensis* R. Baker. Holz als Roh – und Werkstoff, 59:169–175.

Jacquin, P., Mothe, F., Longuetaud, F., Billard, A., Kerfriden, B., Leban, J. M., 2019: CarDen: a software for fast measurement of wood density on increment cores by CT scanning. Computers and Electronics in Agriculture, 156:606–617.

Jones, P. D., Schimleck, L. R., Peter, G. F., Daniels, R. F., Clark, A., 2006: Nondestructive estimation of wood chemical composition of sections of radial wood strips by diffuse reflectance near infrared spectroscopy. Wood Science and Technology, 40:709–720.

Jol, H. M., 2008: Ground penetrating radar theory and applications. Elsevier, 544 p.

Kasal, B., Drdacky, M., Jirovsky, I., 2003: Semi-destructive methods for evaluation of timber structures. In: WIT Transactions on the Built Environment – 2003, p. 835–842.

Kloiber, M., Drdácký, M., Machado, J. S., Piazza, M., Yamaguchi, N., 2015: Prediction of mechanical properties by means of semi-destructive methods: A review. Construction and Building Materials, 101:1215–1234.

Kloppenburg, A., 2018: Density determination of tropical hardwoods with the Resistograph–Diss. Master's Thesis, Delft University of Technology, Delft, Netherlands, 80 p.

Kowal, J., Karwat, B., Sioma, A., 2012: Using three-dimensional images in the description of environment and biological structures. Polish Journal of Environmental Studies, 21:227–232.

Ku, G., Wang, L. V., 2001: Scanning microwave-induced thermoacoustic tomography: Signal, resolution, and contrast. Medical Physics, 28:4–10.

Lenz, P., Auty, D., Achim, A., Beaulieu, J., Mackay, J., 2013: Genetic improvement of white spruce mechanical wood traits – early screening by means of acoustic velocity. Forests, 4:575–594.

Lindström, H., Reale, M., Grekin, M., 2009: Using nondestructive testing to assess modulus of elasticity of Pinus sylvestris trees. Scandinavian Journal of Forest Research, 24:247–257.

Liptai, R. G., Harris, D. O., Tatro, C. A., 1972: An introduction to acoustic emission. In: Acoustic Emission. ASTM International, p. 3–10.

Llana, D. F., Hermoso, E., Bobadilla, I., Iñiguez-Gonzalez, G., 2018: Influence of moisture content on the results of penetration and withdrawal resistance measurements on softwoods. Holzforschung, 72:549–555.

Longuetaud, F., Mothe, F., Santenoise, P., Diop, N., Dlouha, J., Fournier, M. et al., 2017: Patterns of within-stem variations in wood specific gravity and water content for five temperate tree species. Annals of Forest Science, 74: 64.

McDonald, K. A., 1978: Lumber Defect Detection by Ultrasonics. Department of Agriculture, Forest Service, Forest products laboratory, Medison, WIS., 23 p.

Meaney, P. M., Goodwin, D., Golnabi, A. H., Zhou, T., Pallone, M., Geimer, S. D. et al., 2012: Clinical microwave tomographic imaging of the calcaneus: A first-in-human case study of two subjects. IEEE Transactions on Biomedical Engineering, 59:3304–3313.

Muller, W., 2003: Timber girder inspection using ground penetrating radar. Insight-Non-Destructive Testing and Condition Monitoring, 45:809–812.

Nicolotti, G., Socco, L. V., Martinis, R., Godio, A., Sambuelli, L., 2003: Application and comparison of three tomographic techniques for detection of decay in trees. Journal of Arboriculture, 29:66–78.

Oja, J., 1997: A comparison between three different methods of measuring knot parameters in Picea abies. Scandinavian Journal of Forest Research, 12:311–315.

Österberg, P., 2009: Wood quality and geometry measurements based on cross section images - Diss. Thesis. Tampere University of Technology, Tampere, 192 p.

Pastorino, M., Randazzo, A., Fedeli, A., Salvadè, A., Poretti, S., Maffongelli, M. et al., 2015: A microwave tomographic system for wood characterization in the forest products industry. Wood Material Science & Engineering, 10:75–85.

Piazza, M., Riggio, M., 2008: Visual strength-grading and NDT of timber in traditional structures. Journal of Building Appraisal, 3:267–296.

Pirouz, Z., 2015: Defect Detection Technology for Hardwood Manufacturing, FP Innovations, 85 p.

Rais, A., Ursella, E., Vicario, E., Giudiceandrea, F., 2017: The use of the first industrial X–ray CT scanner increases the lumber recovery value: case study on visually strength-graded Douglas-fir timber. Annals of Forest Science, 74:28.

Riggio, M., Anthony, R. W., Augelli, F., Kasal, B., Lechner, T., Muller, W. et al., 2014: In situ assessment of structural timber using non-destructive techniques. Materials and Structures, 47:749–766.

Rinn, F., Schweingruber, F. H., Schär, E., 1996: Resistograph and X–ray density charts of wood. Comparative evaluation of drill resistance profiles and X–ray density charts of different wood species. Holzforschung, 50:303–311.

Rosenthal, A., Jetzfellner, T., Razansky, D., Ntziachristos, V., 2012: Efficient framework for model-based tomographic image reconstruction using wavelet packets. IEEE Transactions on Medical Imaging, 31:1346–1357

Ross, R. J., Brashew, B. K., Pellerin, R. F., 1998: Nondestructive evaluation of wood. Forest Products Journal, 48:14.

Ross, R. J., 2015: Nondestructive evaluation of wood: second edition. General Technical Report, Madison, WI: U.S. Forest Service, 169 p.

Sandak, J., Tanaka, C., 2005: Evaluation of surface smoothness using a light-sectioning shadow scanner. Journal of Wood Science, 51:270–273.

Sauter, U. H., Bruechert, F., Straudenmaier, J., 2017: Nondestructive Assessment of Wood Quality throughout Wood Supply Chain and Manufacturing Process In: Wang, X.; Senalik, C. A.; Ross, R. J., (eds.): 20th international nondestructive testing and evaluation of wood symposium. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory, p. 8–13.

Senalik, C. A., Wacker, J. P., Wang, X., Jalinoos, F., 2016: Assessing the ability of ground-penetrating radar to detect fungal decay in Douglas-fir beams. In: 25th ASNT Research Symposium – 2016, New Orleans, p. 110–116.

Simic, K., Gendvilas, V., O'Reilly, C., Harte, A. M., 2019: Predicting structural timber grade-determining properties using acoustic and density measurements on young Sitka spruce trees and logs. Holzforschung, 73:139–149.

Sioma, A., 2015: Assessment of wood surface defects based on 3D image analysis. Wood Research, 60:339–350.

Schimleck, L., Dahlen, J., Apiolaza, L. A., Downes, G., Emms, G., Evans, R. et al., 2019: Non-destructive evaluation techniques and what they tell us about wood property variation. Forests, 10:728.

Schimleck, L. R., Evans, R., Matheson, A. C., 2002: Estimation of Pinus radiata D. Don clear wood properties by near-infrared spectroscopy. Journal of Wood Science, 48:132–137.

Schmoldt, D. L., Occeña, L. G., Lynn Abbott, A., Gupta, N. K., 1998: Nondestructive evaluation of hardwood logs: CT scanning, machine vision and data utilization. Nondestructive Testing and Evaluation, 15:279–309.

Sonka, M., Hlavac, V., Boyle, R., 2014: Image processing, analysis, and machine vision. Cengage Learning, 920 p.

Stängle, S. M., Brüchert, F., Heikkila, A., Usenius, T., Usenius, A., Sauter, U. H., 2015: Potentially increased sawmill yield from hardwoods using X–ray computed tomography for knot detection. Annals of Forest Science, 72:57–65.

Thomas, L., Mili, L., Thomas, E., Shaffer, C. A., 2007: Defect detection on hardwood logs using laser scanning. Wood and Fiber Science, 38:682–695.

Thumm, A., Riddell, M., Nanayakkara, B., Harrington, J., Meder, R., 2010: Near infrared hyperspectral imaging applied to mapping chemical composition in wood samples. Journal of Near Infrared Spectroscopy, 18:507–515.

Tiuri, M., Heikkilä, S., 1979: Microwave Instrument for Accurate Moisture Measurement of Timber. In: 9th European Microwave Conference – 1979, Brighton, p. 702–705

Wang, X., Ross, R. J., 2002: Non-destructive Evaluation of Green Materials – Recent Research and Development Activities. In: Nondestructive evaluation of wood. Forest Products Society, Madison, p. 149–171.

Wang, X., Divos, F., Pilon, C., Brashaw, B. K., Ross, R. J., Pellerin, R. F., 2004: Assessment of decay in standing timber using stress wave timing nondestructive evaluation tools. US Department of Agriculture, Forest Products Laboratory, Technical Report, 147 p.

Wang, J., Zhao, Z., Song, J., Nie, Z. P., Liu, Q. H., 2013: Reconstruction of microwave absorption of multiple tumors in heterogeneous tissue for microwave-induced thermo-acoustic tomography. Progress, Electromagnetics Research, 32:57–72.

Wen, J., Gao, L., Xiao, X., Xiao, Z., Li, C., 2016: Detection and measurement of internal defects for treetrunk by GPR. International Journal of Simulation: Systems, Science and Technology, 17:9–1.

Zhang, D., He, H., Zong, C., Liu, Y., 2019: Microwave-induced thermoacoustic imaging of wood: a first demonstration. Wood Science and Technology, 53:1223–1234.

Internet sources:

FAKOPP., 2020: Manual for the ArborSonic3D acoustic tomograph. [Brochure], Available at: https://fakopp.com/en/product/arborsonic/

Microtec, 2019: CT Log Computed Tomography for the sawmill of the future. [Brochure], Available at: https://microtec.eu/assets/products/ctlog/MT-CT-Log2.pdf

Sensors & Software. 2016: pulseEKKO - For the GPR Professional [Brochure], Available at: https://www.sensoft.ca/wp-content/uploads/2016/02/pulseEKKO-Brochure.pdf

Ward, C., 2014: SilviScan™ rapid wood analysis, CSIROpedia. Available at: https://csiropedia.csiro.au/SilviScan-rapid-wood-analysis/ry

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Forest educators as bearers and implementers of deep ecology ideas

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Abstract

People think very little about the consequences of consumer and ecological manners. Responsibility for raising children to sustainable behaviour is transmitted to educational institutions that bear the full weight of this burden. Non-teaching experts such as foresters enter the educational process. These specialists are called "forest educators". At the 14th European Forest Pedagogics Congress 2019 in Latvia, 167 forest educators from Europe met, and 52 of them were willing to participate in a qualitative research survey. This paper aimed to identify why foresters, as people without pedagogical education and despite the unfavourable funding, become educators. The following questions guided this research: What leads them to start organizing educational and adventure programmes for children and the public? Is their intrinsic motivation based on an unconscious level to implement ideas of Deep Ecology? Philosophy of Arne Naess and semi-structured interviews with forest educators in the form of the Pyramid Model of Wengraf, through which qualitative data were obtained, methodologically approached this paper. Interviews with foresters revealed their values, needs, motivation, dominant psychological-ethical moments and prosocial behaviour that brings inner satisfaction and pedagogical activity as an added value of their profession. Forest educators have a unique philosophical system related to nature and the environment. They subconsciously follow and develop the ideas of Deep Ecology through the methods of Forest Pedagogy. The paper presents the way of involving forest educators into the distance and online teaching due to the Coronavirus pandemic, as well as the topic for further research in this area.

Key words: Arne Naess; ecosophy; education for the 21st century; Forest Pedagogy online; Wengraf Pyramid model

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1. Introduction

The cause of the ecological crisis is due to human attitudes of superiority over nature. The creation of a new harmonious relationship between humans and nature is the goal for a deeply oriented environmental movement, which is associated with the name of the Norwegian philosopher Arne Naess (1912–2009), who considers his ideas as "nonviolent and long-lasting revolution" (Naess 1989, 1993). It seems time has come to resurrect and bring to mind the ideas of Arne Naess, who gave the world a coherent philosophy and the necessary dose of radicality. His appeal seems to be up to date these days.

Modern society is harming the environment. The Value Objectivism characterizes Deep Ecology: animals have value in themselves and the right to live, even though they are not directly useful to humans. Naess (1989) accentuates a universally shared lifestyle that is sustainable without injuring other life forms. Arne Naess's ideas can be well applied in education for the 21st century, which must reflect current global challenges such as climate changes, global economic stability, labour market trends, impending energy crisis, depletion of non-renewable fossil fuels, poverty, and inadequate medical care (Bolstad et al. 2012). Slaughter (1974) states that the long-term intention of the educational system must concern broader social, political, and economic objectives.

Education is the key to make society move towards sustainable and ecological perception (Britto 2017). Dumont et al. (2010) introduce seven principles of learning and teaching for the 21st century. Main pillars are (1) Learners at the centre; (2) The social nature of learning; (3) Emotions are integral to the learning process; (4) Recognizing individual differences; (5) Stretching all students; (6) Assessment for learning; (7) Building horizontal connection. It is precisely the point (3), intuition, emotionality, and empathy, thanks to which, according to Naess (1989), the individual acquires the truth about the world and wisdom.

Naess (1989) considers nature as the best source of knowledge; however, the disadvantage of many environmental education programmes is that they show nature

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from an adult perspective, which is too abstracted for the child's perception in the early years. Naess suggests that the essential tool for the knowledge of nature is the non-rational form of cognition, empathy, identification through emotions, not through reason. Humans perceive nature by empathy more objectively than scientifically. That is the reason why education should consist of events and creative activities; there is not a sharp line between learning and action (Naess 1989, 1993). How we relate to nature is a matter of feeling, so Naess recommends getting feelings into learning as well and emphasizes that feelings have cognitive value (Devall & Sessions 2007). This point of view is supported by Wedlichová (2011): sensory experiences can increase emotional intelligence in children.

Environmental education and training for sustainable behaviour are closely related to the natural environment. We can hardly find a better example of sustainable management for centuries than in forestry. In nature, it is the best to demonstrate methods to improve sustainable development and environmental education. Slee (2001) considers forest to be a natural framework, essential for human existence and development as forests perform many functions-protective, medicinal, economic, recreational, and educational. Could it be the reason why foresters enter the educational process?

Forest Pedagogy represents neoteric sustainability education that corresponds to the philosophy of Deep Ecology, affecting emotions, will, and awareness. The basic principle of Forest Pedagogy is the perception of nature by all senses, according to Pestalozzi's concept of "learning with head, heart, and hand" (Kuhlemann & Brühlmeier 2002). Cornell (1991, 1998, 2012) qualifies Forest Pedagogy as a form of public relations and social phenomenon that includes environmental education, institutions, associations, forest schools and describes four levels of experience: awakening enthusiasm, focusing attention, direct experience, and sharing inspiration.

The term "forest educator" is currently used and unified in the international forest environment and means a Forest Pedagogy Lecturer as a professional forester with pedagogical education gained by a particular course. Experts with forestry education or experience in forestry who have completed a Forest Pedagogy course accredited by the relevant Ministry of Agriculture of the given state can become forest educators. Forest Pedagogy courses are of two types and take 40 hours each. The introductory one, where foresters learn the fundamentals of pedagogy, psychology and didactics, and are trained to work with class groups of kindergartens, primary and secondary schools. The advanced course is intended for graduates of the introductory course and expands the target groups by adults, seniors and groups with special educational needs. Forest Pedagogy courses are compatible with courses in other European countries and are based on the outputs of the European project PAWS (Pädagogische Arbeit im Wald).

The common goal of foresters and teachers should be to organize a lesson in which pupils better understand the context of nature. The forest would serve as a unique classroom, combining the experience of the forester with the teacher's expertise. This approach connects pedagogy-experience and nature (Machar 2009), where pupils meet their teachers working as a team member and gain valuable social experience. Stern et al. (2010) revealed that specific characteristics of teachers, particularly enthusiasm, interest in the matter, sincerity and charisma, are strongly associated with more positive pupils achievements. Other authors support the importance of demonstrating genuine care of students (Russel 2000; Ballantyne et al. 2001; Fien & Packer 2001) and providing a holistic experience (Tilden 1957; Skibins et al. 2012). Stern et al. (2008) found that when teachers are actively involved in on-site lessons with instructors, students' outcomes are generally more positive. The findings suggest that teachers and other adults play a crucial role in environmental literacy development (Emmons 1997; Rickinson 2001; Sivek 2002; Stern et al. 2008, 2010).

Increasing aggression of children and heavy mental burden accompany the educational process. Children are alienated from nature, showing no interest in education (Mazáčová 2001; Bajtoš & Honzíková 2007). Burnout often occurs in the teaching profession, and the education sector is often under-funded in many countries. Liu et al. (2000) reported that in the USA teaching is a significantly less prestigious profession than others in terms of income, with teachers earning *among the lowest annual salaries of their college cohort* (Henke et al. 2000, as cited in Liu et al. 2000). Teachers work under the scrutiny of parents and the media without sufficient job satisfaction (Spear et al. 2000; Lai et al. 2001; Hoyle 2008). Much of the existing literature on teachers' motivation to teach coming from western countries found teachers to be motivated mainly by intrinsic and altruistic motives such as nurturing students' growth (Sinclair 2008). They believe they contribute to society and may consider teaching as a vocation (Spear et al. 2000; Scott et al. 2001; Richardson & Watt 2006; Alexander 2008).

This paper aims to identify why foresters, as people without pedagogical education and despite the unfavourable financial valuation, become educators. The following questions guided the research: What made them start organizing educational and adventure programmes? Is their intrinsic motivation based on an unconscious level to implement ideas of Deep Ecology? Semi-structured interviews methodologically approached this topic with forest educators in the form of the Pyramid Model of Wengraf, through which qualitative data were obtained.

The results may contribute to understanding better the content of work, formal and legal issues as well as employment conditions of forest educators and improve their relations with teachers. Education is an integral part of forestry, in particular as forest tenure changes, and now the share of private forest ownership is large. The growing public interest in the recreational function of the forest makes forest education now more crucial than ever.

2. Material and methods

In recent years, there has been an increase in new criteria to assess the quality of qualitative research. In a plethora of modern terms, many modern concepts can be found such as imperial validity, ironic validity, situational validity, neopragmatism validity, rhizomatic validity, overt validity, instrumental validity, or theoretical validity (Altheide & Johnson 1994). Based on the above, the qualitative research was carried out, as qualitative data naturally describe the situation and aims to understand people and the events in their lives (Gavora 2008). The interviewee fully expresses subjective opinions and indicates relations and contexts (Hendl 2016). Qualitative research is not based on any hypothesis or theory but tries to outline a new theory (Švaříček & Šeďová 2007). The advantage of the interview is also a significantly higher proportion of completed interviews compared to the return rate of the questionnaires, and also the possibility to clarify responses which have not been previously appropriately understood and the researcher is sure to speak to the intended person (Disman 2002). In this paper, the method of the in-depth individual semi-structured interview was applied. The Pyramid Model of the interview was used to create the interview scheme (Wengraf 2001). This model consisted of a central research question, theory questions, and particular interview questions.

2.1. Research sample

The first criterion was that all of the respondents for qualitative research were forest educators actively pursuing their profession. The second criterion was an international comparison. An available opportunity was the 14th European Forest Pedagogics Congress 2019 in Riga, Latvia, with international participation of one hundred sixty-seven forest educators from eighteen European countries. The third criterion was the diversity of organizations in which forest educators operate, i.e. Urban or State Forests, Forest Learning Centers, Environmental Centers, and Youth Homes.

The research sample included fifty-two active forest educators from various forestry organizations from five regions of the Czech Republic (18), as well as foresters from Finland (2), Norway (3), Latvia (9), Germany (5), Poland (3), Slovakia (4), Slovenia (3), Luxembourg (5) and other countries. The qualitative data collection was in progress from 1st July to 31st October 2019 during the congress, and after its completion, interviews with forest educators took place via Google Meet and Microsoft Teams online. Subsequently, the text was submitted to the respondents for authorization.

The structure of questions according to the Pyramid Wengraf model (2001) is as follows:

The main research question
What made foresters become educators, what does the profession bring to them and what motivates them?

Specific Research Question 1
What work experience and education did the foresters have before they become educators?
- Forestry education,
- pedagogical education,
- previous experience from leisure activities.

Specific Research Question 2
What influenced the decision of the forest educator to choose his new professional focus?
- Previous positions,
- financial remuneration,
- other reasons.

Specific Research Question 3
How do forest educators perceive their profession?
- Positives and negatives,
- how should ideal forest educator look like?

Probing, based on questions and non-verbal hints, was used to deepen answers in a particular direction. A problem-oriented interview, tailored to the research goal was conducted. Transcripts of interviews were transformed and interpreted to capture the complexity of the examined phenomenon. The Open coding for data evaluation and the ATLAS.ti programmes were used, where each significant sentence, word, or phrase, was highlighted and assigned a code representing the essence of the text. According to the codes, information was compared to each other, merging and integrating similar and related semantic units.

3. Results

On the answers obtained from the interviews conducted according to the Pyramid Model by Wengraf (2001), data were analyzed and interpreted.

3.1. Education and professional experience of forest educators

3.1.1 Forest Education

Almost all (49) forest educators addressed have a forestry education and completed a course in Forest Pedagogy, which is an essential condition for practising this profession. A minimal number of foresters (3) do not have a forestry education, which is compensated by no less than ten years of experience in environmental education centres.

3.1.2 Pedagogical education

All respondents (52) are graduates at least an introductory Forest Pedagogy course. More than half of them (38) also have a certificate from the extension course. Everyone confirms that the course is beneficial, as they know the basics of didactics, psychology, have the opportunity to meet new colleagues and acquire inspiration for future work. Forest educators mostly agree that *without the basics of developmental psychology and the basics of pedagogy, I would probably not know how to engage children.* Sixteen foresters already have a bachelor‘s pedagogical education obtained in college. Four of them are currently studying vocational subjects or leisure-time education. Foresters who are interested in further pedagogical education are those for whom Forest Pedagogy takes up more than half of their working time. Foresters who provide Forest Pedagogy activities beyond their work duties, do not consider the further pedagogical study. However, they all agree that the basics of pedagogy, psychology, and didactics are desirable. Otherwise, this would affect the quality of the programmes.

3.1.3 Free-time pedagogy

Most forest educators have been interested in nature, experiential education, and children since their youth, as head of children‘s camps, Scout, or another organization. One answer for all: *As a child, I liked going to summer camps in the countryside, and I am glad that I can bring this hobby to my job as well.* Most of the respondents (46) have tacit knowledge in organizing leisure and free-time activities.

3.2. What influenced the decision to become a forest educator

Only a third of the foresters (17) carried out this activity on a full-time basis and had to leave their existing post. The others focus on the main content of the work, such as forest recreational function, forest protection, or forest management, so their pedagogical activities take up only part of their working time. Respondents often spend free time preparing Forest Pedagogy activities and do it beyond their job, in many cases for free or for a symbolic allowance only. Especially the statements of the Czech and Slovak forest educators show that the management of forest enterprises prefers *non*-pedagogical content of work.

3.2.1 Previous employment

The previous job position remains, and educational activity is included in addition. The scenario prevails, where foresters participated in environmental and leisure activities (Scout, Forest Pedagogy course) and the supervisor then offered them the opportunity to attend the course and become a forest educator.

3.2.2 Financial aspect

Forest educators coincide that salaries did not play a role in their decision-making. One forest educator describes it as follows: *It is not possible to get rich in Forest Pedagogy. When it becomes a business, enthusiasm is lost.* At present, in many European countries, the profession of a forest educator is not well-paid for generating a separate full income. Thanks to these facts, it is not appropriate to expect the forester to perceive Forest Pedagogy as a profession, but rather as a hobby, especially in the post-communist countries where Forest Pedagogy does not have such a tradition.

3.2.3 *Raison d‘etre* for Forest Pedagogy

The vast majority of forest educators say this is due to the variety and creativity of their profession. They praise not to have office work, duties are diverse, and the job brings satisfaction. There are considerable differences between countries.

Forest educators from Austria state that although in their country forest education courses are open to all interested, only a graduate with forestry education receive the certificate and only the certificate holder can be financially supported.

Polish forest educators report that at least one full-time forest educator is available at each forest administration in Poland and offers four follow-up programmes for each season. The average Polish Baccalaureate attends, on average, thirty Forest Pedagogy lessons. It may affect young people in the future on Forest Pedagogy.

Estonians are considered “forest nation” and want to raise awareness about the forest among the public, especially in preschool children, and find many candidates interested during the Forest Weeks.

Foresters from Finland are also motivated by material reasons: there are many forest owners in Finland, and every sixth schoolchild is expected to own the forest in the future, so children should be informed about it. To educate the schoolchild, efforts to engage teachers and so the Finnish Forestry Association, together with teachers, created publications and websites to support teaching at schools.

The situation in the Czech Republic is significantly different. A frequently mentioned reason for forest educators from the Czech Republic is the possibility to “clarify” the forestry and forester‘s reputation negatively affected by media and to provide nature-oriented upbringing and awareness-raising. Forest Pedagogy is one of the ways to attract people to the forest and also to improve the image of forestry. A curious reason for being a forest educator was mentioned by one female, who received the answer to the question: “Who is the most significant pest in the forest?" Answer: *Forester*. It was precisely the moment when she decided to change the image of forestry in the eyes of the general public in the Czech Republic.

3.3. Perception of Forest Pedagogy

Distinctions between countries are evident. Each forest educator devotes to Forest Pedagogy and educational programmes in another way and has different time and financial support, which are based on how a particular forestry enterprise approaches Forest Pedagogy.

3.3.1 Pros and Cons of Forest Pedagogy

All respondents agreed that the most considerable advantage of Forest Pedagogy is the possibility to get people into the countryside, to familiarize them with the forest environment, what is in line with Forest Pedagogy goals (Harkabus & Marušáková 2007). Forest educators can arrange the programmes, be it a theme, games, activities, or a place to go and appreciate having contact with new people and the possibility of self-education, socialization, and self-realization. They mostly appreciate attending seminars, lectures, and meetings organized for forest educators where they can learn and inspire. Young female forest educators expect to gain experience and skills in activities with children in nature, which they can use in raising their kids. They see what today-kids are missing.

Half of the forest educators prepare programmes and materials during free time. Almost half of the respondents regret not to have sufficient financial or moral support at their employers. Forest educators, especially from the former post-communist states, repeatedly complained that the public does not appreciate their work and considers it inferior. Many professional foresters look at their colleagues with absolute disrespect. They consider Forest Pedagogy to be entertainment only. Another disadvantage is that forest educator has no chance to get to know the children accurately in a short period, and cannot cooperate with them in contrast to regular leisure activities or school lessons.

To respond to the question of whether the foresters lost something in carrying out their educational activities, embarrassing answers were received. Some admit that this activity deprives them of illusions, mainly of teachers' cooperation with them and how some teachers treat children and foresters. Following are presented the words of one forester: *I think that teachers are afraid to "hand over" their pupils to us as if they are afraid of losing control and power. Sometimes the teacher comes in a bad mood, and his current mental state is unfortunately passed on to children. They are then bored, and it is complicated to master the discipline.* This experience was repeated: *When several classes came at the same time, the teachers stood apart and talked among themselves and showed no interest in the pupils. I was then very disappointed that the teachers wrote a critical assessment, not even knowing what was happening around.* Many forest educators have lost their expectations about the basic knowledge of the public about forest and nature and the respect that people should have for nature.

3.3.2 The idea of an ideal forest educator

The final question of the interview concerns the characteristics, abilities, experience, and education of ideal forest educator should have. Two streams of opinion emerge from the respondents' answers. Twenty-seven would appreciate practising Forest Pedagogy at full-time: *I would have time to refresh content, innovate games, have more scope and support. Collaboration with schools could be planned and implemented in the long term without the risk of any other event interfering with the plan.*

However, the other half (25) of forest educators strongly disagree with this and believe that foresters should only do this part-time. They are satisfied that they do not have to do educational plans every day and are engaged in other activities, and Forest Pedagogy does not become a routine matter. There is also an opinion that: *Forest educator is not an independent profession and should not be in the future. It is something in addition to the professional forest focus.*

4. Discussion

Forest educators are introduced as professional foresters with pedagogical education gained by a particular course (Cornell 1991; Bolay & Reichle 2007). There is no relevant article or study that would examine in more detail the reasons and motives of foresters, why they voluntarily and despite the low funding undertake pedagogical courses so that they can act as teachers of their kind.

The paper aimed to identify why foresters enter the educational process and if their intrinsic motivation is based on the subconscious level of Deep Ecology thinking. Interviews showed that foresters have a specific personal framework of values related to human and nature issues. For forest educators, ecology is not just a theory but a deep conviction. They are probably not even aware, their stance to life reflects a deep ecological feeling that has roots in A. Naesse's conception. Forest educators try to pass on the depth of knowledge and experience, live in nature and with nature, not just visit it. They show the public how to move in the forest without consequences, respecting all life forms, not just those beautiful, remarkable, or useful. They teach not to use living beings only as a resource; leading to the recognition of their intrinsic value. Forest educators protect the forest ecosystem as a whole, not just individual life forms and show that people living in urban areas can be connected with nature even in a disturbed environment, as parts of green can be found everywhere. The ideas of Deep Ecology are based on these rudiments (Naess 1989, 1993).

Why do foresters engage in education despite many obstacles, misunderstandings and inadequate funding?

One of the reasons is the general effort of foresters to explain objectively the distorted information disseminated by the media relating the bark beetle calamity. All the foresters addressed agree that they have the honour to carry out highly professional activities for nature and future generations and do it with enthusiasm, even if the result of their effort is difficult to measure. Foresters believe their activities have a deeper meaning. Interest, a positive attitude to nature, and self-realization force them to go forward. Their job offers an opportunity for the initiative, responsibility, and knowledge growth. Foresters consider their calling essential and are willing to devote to it, although they often do not get extra money for their endeavour. The profession of forest educator has a psychological-ethical moment-the chance to educate someone else is perceived as a reward. Forest educators consider as a substantial intrinsic value of the job to broaden horizons for someone else and to expand the moral compass. The above is consistent with the motives of intrinsic motivation presented by Dieblová (2005).

Forest educators understand the context of nature very well, their tacit knowledge goes beyond school textbooks of natural history, and they could be a functional link between the public and the natural ecosystem. Based on strong inner convictions and enthusiasm, it is recommended to involve them in school curricula to provide transmission of knowledge and experience to children. The content of School Education Programmes can be arranged in the school curriculum in coherent parts, such as modules or blocks using parallel support by close cooperation with a local forest centre.

The Coronavirus pandemic increases the demands on the form and methodology of teaching. The Ministries of Education of the affected states now more recommend including full-time educational activities held in the school garden, playground, park and school surroundings, where there is no accumulation of more people in order to reduce epidemiological risks, improve the overall health, concentration and well-being of pupils and teachers. Many parents and teachers perceive outdoor learning as too risky and unsafe. The presence of a forest educator, as an expert on a stay in nature, should eliminate the concerns of parents.

In pandemically affected areas, pupils are not present at school and are educated synchronously and asynchronously. There is also a new dimension for the online inclusion of forest educators into the teaching process of those subjects that have nature and science as a basis. A forest educator wearing a livery can engage children with his demeanour, speech, personal example, positive attitude and commitment. The forest-dressed educator does not fit into uniformity of civilian teachers and can pass on knowledge and context of a different dimension than the science teacher could. Forest Pedagogy methods can also be manifested in the distance form; the forest educator assigns tasks, for which pupils have to get out in nature and together with their classmates in the online forum share their experiences of the forest. The growing ability to recognize the signs of upcoming changes in the forest that children would report to the forester could be regarded as an added value. The looming negative phenomena in the forest can thus be identified and resolved at the beginning. Even if only one child is enthusiastic about this idea, it would be a significant help to foresters, who, due to the scale of their activities, may not always be able to detect all changes in their district immediately. This way of teaching could help and solve the problem even for teachers who do not support outdoor activities.

5. Conclusion

Involving professionals into education is desirable and beneficial-due to the differences between learning about versus learning from an expert (Berliner 2001; Guskey & Yoon 2009). Children are not passive recipients only, they are often the initiators of new manners, and by constituting their relationship to nature, it is realistic to expect the effect that is secondarily transmitted on parents.

The involvement of forest educators in distance teaching will be the theme of further research survey, where the Experimental group (online tuition with forest educator) would be compared with the Control group (distance education by the teacher) through a didactic test.

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References

Alexander, P. A., 2008: Charting the course for the teaching profession: The energizing and sustaining role of motivational forces. Learning & Instruction, 18: 483–491.

Altheide, D. L., Johnson, J. M., 1994: Criteria for assessing interpretive validity in qualitative research. In: Denzin, N. K., Lincoln, Y. S. (eds.): Handbook of qualitative research. Thousand Oaks, Sage, p. 485– 499.

Bajtoš, J., Honzíkova, J., 2007: Vybrané statě školní pedagogiky. Plzeň, Západočeská univerzita v Plzni., 192 p.

Ballantyne, R., J. Fien., J. Packer., 2001: School Environmental Education Programmesme Impacts upon Student and Family Learning: A Case Study Analysis. Environmental Education Research, 7:23–37.

Berliner, D. C., 2001: Learning about and learning from expert teachers. International Journal of Educational Research, 35:463–482.

Bolay, E., Reichle, B., 2007: Waldpädagogik. Schneider Verlag: Esslingen, 298 p.

Bolstad, R., Gilbert, J., McDowall, S., Bull, A., Boyd, S., Hipkins, R., 2012: Supporting future-oriented learning and teaching: A New Zealand perspective (Report prepared for the Ministry of Education). Wellington, New Zealand: Ministry of Education.

Britto, P. R., 2017: Early Moments Matter for every child [online]. Published by UNICEF 3 United Nations Plaza, New York, NY 10017, US, Available on: https://www.https://www.unicef.org/media/files/UNICEF_Early_Moments_Matter_for_Every_Child_report.pdf.

Cornell, J., 1991: Mit Kindern die Natur erleben. Mülheim an der Ruhr, Verlag an der Ruhr, 147 p.

Cornell, J., 1998: Sharing Nature With Children. Nevada City, Dawn Publications, 216 p.

Devall, B., Sessions, G., 2007: Deep Ecology: Living as if Nature Mattered. Layton, Utah, Gibbs Smith Publishing, 269 p.

Dieblová M., 2005: Motivace jako nástroj řízení. Praha, Linde, 127 p.

Disman, M., 2002: Jak se vyrábí sociologická znalost. Praha, Karolinum, 374 p.

Dumont, H., Istance, D., Benavides, F., 2010: The Nature of Learning: Using Research to Inspire Practise. OECD Publications.

Emmons, K. M., 1997: Perceptions of the Environment While Exploring the Outdoors: A Case Study in Belize. Environmental Education Research, 3:327–344.

Gavora, P., 2008: Úvod do pedagogického výskumu. Bratislava, Bratislava : Univerzita Komenského, 236 p.

Guskey, T. R., Yoon, K. S., 2009: What Works in Professional Development? Phi Delta Kappan, 90:495–500.

Harkabus, Š., Marušáková, Ľ., 2007: Zásady lesní pedagogiky. In: Učebnice PAWS, p. 64–120.

Hendl, J., 2016: Kvalitativní výzkum: Základní teorie, metody a aplikace. Prague, Portál, 408 p.

Hoyle, E., 2008: Changing conceptions of teaching as a profession: Personal reflections. In: Johnson, D. & Maclean, R. (eds.): Teaching: Professionalisation, Development and Leadership, New York, Springer Science + Business Media B. V., p. 285–304.

Jickling, B., 2005: Deep Ecology and Education: A Conversation with Arne Naess. In: Naess, A., Drengson, A. (eds.): The Selected Works of Arne Naess. Springer, Dordrecht, 1048.

Kuhlemann, G., Brühlmeier, A., 2002: Johann Heinrich Pestalozzi. Schneider-Verlag., 304 p.

Lai, K. C, Mok, A., Ko, K. W., Li., C., 2001: Issues in Teacher Supply and Retention in England and their Implications for Hong Kong. Teacher Education Planning Digest, 6:1–35.

Liu, E., Kardos, S. M., Kauffman, D., Peske, H. G., Johnson, S. M., 2000: Barely Breaking Even: Incentives, Rewards, and the High Costs of Choosing to Teach. 25 p.

Machar, I., 2009: Úvod do ekologie lesa a lesní pedagogiky pro učitele přírodopisu a environmentální výchovy. Olomouc, University of Palacky, 104 p.

Mazáčová, N., 2001: Učitel začátečník. Available on: http://www.ceskaskola.cz/Ceskaskola/Ar.asp?ARI=2869&CAI=2125.

Naess, A., 1989: Ecology, community and lifestyle: Outline of an ecosophy. Cambridge, Cambridge University Press, 223 p.

Naess, A., 1993: How Should Supporters of the Deep Ecology Movement Behave in Order to Affect Society and Culture. The Trumpeter, 10:3.

Rickinson, M., 2001: Learners and Learning in Environmental Education: A Critical Review of the Evidence. Environmental Education Research, 7:307–320.

Russell, C. L., 2000: A Report on an Ontario Secondary School Integrated Environmental Studies Programmes. Canadian Journal of Environmental Education, 5:287–304.

Scott, C., Stone, B., Dinham, S., 2001: I love teaching, but... International patterns of teacher discontent. Education Policy Analysis Archives, 28:1–7.

Sinclair, C., 2008: How can what we know about motivation to teach improve the quality of initial teacher education and practicum? In: Towndrow, P. A., Koh, C., Soon, T. H. (eds.): Motivation and practice for the classroom, Rotterdam, Sense, p. 37–61.

Sivek, D. J., 2002: Environmental Sensitivity among Wisconsin High School Students. Environmental Education Research, 8:155–170.

Skibins, J. C., Powell, R. B., Stern, M. J., 2012: Exploring Empirical Support for Interpretation's Best Practices. Journal of Interpretation Research, 17:25–44.

Slaughter, R., 1974: Futures in education. Futures, p. 341–342.

Slee, R., 2001: Social justice and changing directions in educational research: the case of inclusive education. International Journal of Inclusive Education, p. 167–177.

Spear, M., Gould, K., Lee, B., 2000: Who Would be a Teacher? A Review of Factors Motivating and Demotivating Prospective and Practising Teachers. Slough, UK, National Foundation for Educational Research, 83 p.

Stern, M. J., Powell, P., Ardoin, N., 2010: Evaluating a Constructivist and Culturally Responsive Approach to Environmental Education for Diverse Audiences. Journal of Environmental Education, 42:109–122.

Stern, M. J., Powell, R. B., Ardoin, N., 2008: What Difference Does It Make? Assessing Outcomes from Participation in Residential Environmental Education Programmes. Journal of Environmental Education, 39:31–43.

Švaříček, R., Šeďová, K., 2007: Kvalitativní výzkum v pedagogických vědách. Prague, Portál, 384 p.

Tilden, F., 1957: Interpreting Our Heritage. Chapel Hill: University of North Carolina Press, 191 p.

UNESCO, 1978: Final Report Intergovernmental Conference on Environmental Education, Tbilisi, USSR, 14–26 October 1977. Paris: UNESCO

Wedlichová, I., 2011: Emoční inteligence. Ústí nad Labem, Univerzita J. E. Purkyně, 128 p.

Wengraf, T., 2001: Qualitative Research Interviewing: Biographic Narrative and Semi-Structured Methods. London, Sage, 424 p.

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ORIGINAL PAPER

Postfire tree mortality and fire resistance patterns in pine forests of Ukraine

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Abstract

The study was conducted in pure Scots pine (*Pinus sylvestris* L.) stands within the forest steppe physiographic region of Ukraine damaged by surface fires with different intensity. The aim of the research is to determine the effect of different fire intensity on pine stand and individual trees, considering tree morphometric parameters and type of damage. The intensity and duration of fire-related tree mortality was different in stands with different age. We found that tree fire resistance is driven by tree diameter, height of the rough bark, and natural degree of thickness. The proportion of dead trees one year after the spring fires in the middle-aged pine stands was 5 times lower and in mature pine stands even 10 times lower than after the summer fires. The critical damage to tree crowns in young pine trees causing their death is 80% of the needles burned. In the middle-aged pine trees, critical damage depended on the size of trees. The death of large, mature trees after smoldering summer fires was associated with the accumulation of a large stock of forest litter and duff near the tree-base, which contributed to the increased intensity of fire and its localization near the base part of the trees. Based on our findings, postfire tree mortality models have been developed for different age groups of pine stands.

Key words: surface fires; smoldering fires; postfire mortality models; bark char; crown scorch; season of fire

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1. Introduction

Wildfires are one of the most dangerous factors for forests, leading to their destruction and degradation. Due to global warming and increasing aridity, the risk of increased frequency and extent of wildfires is very high. Many regions of the world have experienced an increasing trend of excessive wildfires and an increasing occurrence of extremely severe fires (FAO 2006).

In 2017, wildfires burnt over 1.2 million hectares of natural lands in the EU. The European Forest Fire Information System estimated the amount of fire-related losses to be around 10 billion Euros (San-Miguel-Ayanz et al. 2017).

In Europe, Scots pine forests now exceed 28 million hectares, covering over 20% of the productive forest area (Mason & Alìa 2000). The most fire hazardous coniferous forests occupy 43% of the total area of Ukraine, in particular, pine stands – 35%, which grow in the North of Ukraine (Polissya) and in the South (Steppe) along the largest rivers, also in the Crimea Peninsula. More than 90% of forest fires in Ukraine occur in pine forests (Voron & Melnyk 2009; Voron & Sydorenko 2014). During the last ten years (2009–2018), 19.9 thousand forest fires have occurred in Ukraine on an area of 37.2 hectares. The economic losses amounted to 8.86 million Euros (Public Report 2017).

The rapid deterioration of the sanitary state of damaged trees leads to significant economic losses due to the decline of stand merchantability and the deterioration of its technical quality. Timely diagnosis and accurate prediction of the postfire trees mortality are thus extremely important. Such studies can mitigate the negative effects of wildfires and will be used to support decisions about forestry treatments in such forests. A considerable amount of research papers is devoted to the prediction of postfire loss of trees for different conifer species (Regelbrugge & Conard 1993; Usenya & Churylo 2001; Fites-Kaufman et al. 2008; Sah et al. 2019). It is well known that the value of postfire mortality rate affects

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the predominant type of damage and fire intensity as well as secondary disturbances such as drought, insects, and diseases (Ahafonov & Alekseev 1989). The research on the impact of fire damage on postfire tree mortality in Ukraine is rather fragmented. The existing diagnostics and predictions of postfire sanitary condition of damaged trees is based on an assessment of the state of tree crowns and visible damages without considering the main factors controlling the fire resistance of trees.

The main goal of this study is to find additional criteria that reflect the intensity of damage and the morphological indicators of fire resistance of pine trees for the development of postfire tree mortality models.

2. Materials and methods

The study was conducted in the pine forests of the forest steppe of Ukraine. The climate is mild, moderately continental. The total precipitation is 546 mm per year^{-1}, of which 38–40% falls during the growing season. The duration of the growing season lasts 205 days. The period with an average daily temperature of +5 °C to +15 °C is 80–90 days. Climatic stress factors (high temperatures in the summer months with the absence of rainfalls, irregular rainfall, long dry periods, evaporation exceeding precipitation) cause repeated occurrence of forest fires.

Study plots (SP) were established in pine stands homogeneous by forest type conditions and stand composition.

The evaluation of fire damage to the tree trunks was determined by the following indicators:

– the bark char height (minimum and maximum), m;
– fire damage of thin (light) bark;
– relative bark char, %;

Relative bark char was determined by the formula [1]:

$$H_{rel} = (H_{m\ char} / H) \times 100\% \qquad [1]$$

where H_{rel} – relative bark char, %; H– height of tree, m; $H_{m\ \mathrm{char}}$ – the maximum height of the bark char, m.

The evaluation of the crown damage was based on the following:

– discoloration, % (the proportion of needles that have lost their natural color, with an accuracy of 10%, no later than a week after the fire damage) (Eichhorn et al. 2010);
– defoliation, % (accuracy up to 10%).

The following tree characteristics were determined: tree height, m; DBH, cm; class of Kraft; height of rough bark, m; number of first-order roots above ground. Natural degrees of thickness (NDT) were additionally calculated for each plantation on the test plots. The date of fire, the date of measurement, the soil condition and the stand age were recorded. We also examined a one-year postfire period, when the intensity of postfire tree mortality was the most intensive.

The sanitary state of the pine stand was characterized by the index of sanitary condition, which was determined by the formula [2] (Sanitary Forests Regulations in Ukraine, 2016):

$$I_c = K_1 \times n_1 + K_2 \times n_2 + K_3 \times n_3 + \ldots K_6 \times n_6 / N \qquad [2]$$

where: I_c – index of sanitary state; $K_1 \ldots K_6$ – category of sanitary state for individual tree (from I to VI); $n_1 \ldots n_6$ – number of trees with specific sanitary category, stems; N – total number of trees on a study plot.

The sanitary state of each tree was determined according to 6 categories (Table 1).

The degree of differentiation of trees in the stand was evaluated according to the Kraft classification (Pogrebnyak 1968):

I – predominant, exceptionally large trees, which dominate the others, have the highest height and diameter and well-developed crowns;
II – dominant trees, which have relatively well-developed crowns and about the same height as class I trees;
III – low co-dominant trees, normally developed, smaller in height than the trees of the previous classes, with less developed, compressed crowns;
IV – dominated trees whose crowns are compressed and the tops reach only the lower part of the crown of the dominant trees;
V – entirely overtopped trees completely under the canopy of dominant trees, far behind in growth and development.

The postfire growth of the damaged trees was investigated on 33 study plots (3 SP in young pine stands, 21 SP in middle-aged and premature stands, and 10 SP in mature and overmature stands). The stands on the SP differed in age and forestry characteristics (Table 2).

Stand structure was characterized by a curve of trees distribution by natural degrees of thickness (NDT). Natural degrees of thickness are an indicator of the tree size by diameter (DBH), expressed in relative proportion of the average diameter of the stand. (Tyurin 1945; Mashkovsky 2015).

Table 1. Criteria for determining the sanitary index of pine stands.

Range of the sanitary index	Needle packing		Needles color	The degree of stand damage
	[%]	distribution of needles on shoots		
1.00–1.50	90–100	without signs of violation	green	absent
1.51–2.50	66–90	without signs of violation	green, light green	weak
2.51–3.50	33–66	clustered	pale green	medium
3.51–4.50	33	clustered	with a yellow tint or yellow-green	strong
4.51–6.00	0	there are no living needles	gray, yellow	very strong
4.51–6.00	0	there are no living needles	—	very strong

Table 2. Characteristics of study plots damaged by surface fires.

No SP	H_{char}, [m]	A [years]	D [cm]	H [m]	M [m^3 ha^{-1}]	Relative density
Yong pine stands						
Summer fires or spring fires						
1	1.20	11	5.3	3.8	9	0.90
2	0.90	11	7.3	4.1	9	0.90
Control	—	11	5.5	4.0	9	0.90
Middle aged stands						
Summer fires						
1	0.69	60	27.2	24.5	386	0.77
2	2.02	57	26.0	21.0	476	1.00
3	2.30	57	21.1	18.7	238	0.58
4	2.52	60	28.4	25.2	481	0.93
5	3.58	68	25.3	20.8	256	0.62
6	4.45	70	26.5	21.2	261	0.62
7	0.78	61	28.6	25.7	268	0.50
8	1.26	61	21.8	19.6	220	0.60
9	1.85	65	28.4	22.2	375	0.91
10	1.98	65	26.6	22.5	401	0.96
11	0.95	65	25.3	23.1	419	0.94
Spring fires						
12	2.05	60	25.8	22.9	384	0.82
13	2.22	60	29.5	23.5	466	0.97
14	3.06	47	24.0	21.8	327	0.74
15	0.20	66	26.3	23.2	411	0.86
16	0.30	59	27.7	22.4	442	0.96
17	0.30	60	29.5	23.1	419	0.88
18	0.80	60	25.8	22.9	380	0.80
19	2.97	60	22.6	21.0	389	0.91
20	2.90	55	17.1	18.5	185	0.88
Mature and overmature						
Spring fires						
21	1.10	81	31.2	23.0	370	0.70
22	3.00	81	37.3	26.2	390	0.60
23	2.33	88	30.1	27.3	642	0.99
24	2.46	88	31.2	24.8	480	0.93
25	1.81	86	34.7	26.0	375	0.69
26	2.40	86	33.2	26.6	476	0.96
27	1.90	86	31.1	25.2	398	0.77
Summer fires						
28	0.48	95	42.6	27.2	361	0.60
29	2.02	116	50.4	31.1	477	0.72
30	2.16	116	42.6	29.8	385	0.60

Note: SP – sampling plot; H_{char} – the average height of the bark char, m; A – age; D – diameter; H – height; M – stock volume per 1 ha.

Classification of pine stands by age group was performed according to the following criteria (Svyrydenko et al. 2004):

– young (pine stands up to 40 years old);
– middle-aged (41 to 80 years old);
– premature stands (from 81 to 90 years);
– mature and overmature (over 90 years old).

Tree resistance was assessed using Pearson's correlation. Correlation analysis was used to assess possible linear associations between tree sanitary index and potential variables that reflect fire resistance: DBH (diameter at breast height), NDT, tree height, tree age, bark thickness, rough bark height, etc.

Multiple regression analysis as well as logistic regression analysis (binary regression) were used to construct predictive models for the tree mortality probability of individual trees. The use of logistic regression is appropriate to determine the likelihood of individual trees mortality. Logistic regression quality and accuracy were tested by ROC analysis using IBM's SPSS 20. For the analysis of model quality and its cut-off threshold correction ROC-analysis (receiver operating characteristic) was used. In ROC-analysis, model quality is considered to be excellent at AUC (area under curve) value 0.9–1.0; very good at 0.8–0.9; good at 0.7–0.8; average at 0.6–0.7; poor at 0.5–0.6 (Fawcett 2004).

While studying the influence of Kraft class (KC) on the resistance to fire damage of trees with the same height of bark char, a sampling of trees was selected from the whole set of trees within the range of bark char height 0.51–1.00 m differing in KC. Despite a small number of I–II and IV–V KC trees, they were joined into groups: I–II, III and IV–V KC. One-way ANOVA was used. The power of the influence of the factor was determined by the method of Plokhinsky (Lakyn 1990).

3. Results

3.1. Postfire tree mortality in the young pine stands

A significant correlation ($r = 0.92$; $p = 0.05$) was found between the level of discoloration and the sanitary condition of the trees. The highest intensity of mortality was determined in the year of the fire, when 23.8% of the total number of trees. In the following year, the mortality rate decreased, reaching 5.6% of trees, and 1.7% of trees in the third year after the fire.

It has been found that the lethal level of damage to young pine trees is achieved when the relative bark char ($H_{rel.}$) reaches 61–70%. In this case, mortality reaches 82% of trees, corresponding with the 80% of the growing stock (Table 3).

Small damages of tree crowns (up to 30%) did not lead to tree mortality. Significant deterioration of the sanitary state with the subsequent death of a significant number of trees was observed in the case of a severe damage to the crown – more than 81%. Trees with over 91% damage to the crown died within a year after the fire.

Table 3. Distribution of dead trees depending on the type and value level of damage in the pine young stands of Vasyshchevske Forestry, State Enterprise Zhovtneve, Kharkiv region.

The value of damage [%]	Proportion of dead trees [%]			
	$H_{rel.}$ [%]		D [%]	
	N	M	N	M
0–10	6	1	—	—
11–20	7	1	—	—
21–30	8	1	—	—
31–40	25	20	—	—
41–50	35	32	—	—
51–60	71	75	—	—
61–70	82	80	3	1
71–80	—	—	4	1
81–90	—	—	38	42
91–100	94	92	94	96

Note: $H_{rel.}$ – relative bark char, %; D – crown discoloration, %; N – number of trees, stems, %; M – percent of the stock, %.

Larger pine trees were more fire resistant. Characteristics such as diameter, height and class of Kraft were the best indicators of fire resistance in young pine stands.

It has been confirmed that a model that considers tree diameter, relative bark char, and crown discoloration (AUC = 0.95 ± 0.012) performs best in predicting the probability of tree mortality.

A simplified version of model, which included only the magnitude of crown discoloration, had an AUC value of 0.93 ± 0.014. Both models have "excellent" quality in classification (Fawcett 2004), so we suggest to use the simplified model (3) that includes discoloration and predicts postfire mortality with an accuracy of 89.9%. This model correctly predicts the postfire status of surviving trees with an accuracy of up to 94.3% and of dead trees up to 80%. The risk of trees mortality is extremely high with a discoloration of over 80%.

$$P = \frac{exp\ (-9.095 +\ 0.111 \times D)}{(1 +\ exp\ (-9.095 +\ 0.111 \times D)'} \qquad [3]$$

where P is the probability of postfire mortality; D – crown discoloration,%.

3.2. Postfire tree mortality in the middle-aged pine stands

Middle aged middle-aged pine trees were found to be characterized by an increase in fire resistance of trees with an increase in trunk diameter (a correlation between the diameter and the sanitary condition of damaged trees was revealed: r = –0.4; p = 0.05).

Stands with the same level of damage caused during fires that occurred in different seasons of the year were exhibiting different intensity of mortality. We found that mortality rate after summer fires can be 10 times higher than after spring fires. Trees with the same value of damage (mean height of bark char) and age but damaged in different seasons had a different reaction to fire damage. The index of sanitary state after spring fires was 2.48; after summer fires – 4.4 (ANOVA results: $F_f = 79.8$ and $F_{0.001} = 12.4$, $h^2 = 0.77$).

After spring fires, the index of sanitary state, even with significant damage to the trunk (bark char height above 4 m), ranged from 2.6 to 2.8 (weakened stand). After the spring surface fires, only Kraft class IV–V trees died out. The percentage of dead trees increased in stands with a larger proportion of IV and V Class Kraft (CK) trees. Thus, in damaged pine trees, the fire accelerated the natural liquefaction of the stands. The significance of the influence of the investigated factor was proved by comparing trees that are homogeneous in their level of damage and taxation characteristics but different in Kraft classes ($F_f = 6.47$; $F_{0.05} = 4.88$).

A strong direct relationship between the bark char on the tree trunks and the sanitary state of the trees was established (r = 0.91, $t_f = 6.80$, $t_{0.01} = 3.17$). The results of the regression analysis show that in 83% of cases after summer fires, the sanitary state of trees is determined by the average bark char on trees. It was also proved the proportion of dead trees after the fire in the studied tree groups increases in response to the increasing average height of the bark char (r = 0.87, $t_f = 5.80$, $t_{0.01} = 3.17$) (Fig. 1).

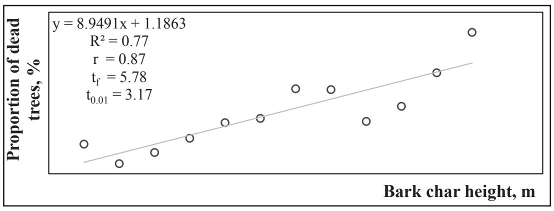

Fig. 1. Relationship between the proportion of dead trees and average bark char height on the trunks in middle-aged pine stands damaged by surface fires in summer.

The postfire models were further improved by considering the distribution of trees by NDT (ranking trees in the planting relative to the average diameter) that contains both the class of tree development (Kraft class) in the stand and its size (diameter). A negative correlation (r = −0.54; p = 0.05) was found between the sanitary state and the NDT; a less close relationship was found between the diameters and the sanitary condition of the trees (r = 0.40; p = 0, 05).

For NDT 0.7–1.2, lethal damage occurs at the height of up to 3 m on the trunk (the index of sanitary state reaching 4.1–4.6). For trees with NDT more than 1.3, lethal damage is achieved only if the height of bark char exceeds 4 m (Table 4).

Table 4. Proportion of dead trees depending on the natural degrees of thickness and average bark char height after summer surface fires.

H_{char} [m]	NDT					
	>0.6	0.7–0.8	0.9–1.0	1.1–1.2	1.3–1.4	1.5>
>1.0	22	11	8	1	0	0
1.1–2.0	47	12	10	1	0	0
2.1–3.0	71	30	34	3	9	—
3.1–4.0	75	42	41	29	0	—
4.1>	—	100	43	36	40	33

Note: H_{char} – m; NDT – natural degree of thickness.

An increase in the proportion of dead trees with the increasing average height of bark char was detected in the groups of trees that were different in NDT and the average height of bark char. The group of trees depressed in growth (NDT 0.5–0.7) is characterized by an extremely high proportion of dead trees, which increases rapidly (from 22 to 75%) with the growth of damage intensity. For trees with the NDT of 0.7–1.0, the critical bark char height is more than 2 m (the share of dead trees comprises 30–34%).

The best performing models based on the logistic regression analysis included the natural degree of thickness and the average bark char height (H_{char}) (Fig. 2) (4).

$$P = \frac{\exp(2.67 - 5.20 \times NDT + 0.61 \times H_{cep})}{(1 - \exp(2.67 - 5.20 \times NDT + 0.61 \times H_{cep}))'} \qquad [4]$$

where P stands for the probability of postfire tree mortality (from 0 to 1); NDT is the natural degree of thickness; H_{char} is the average bark char height on the tree trunks.

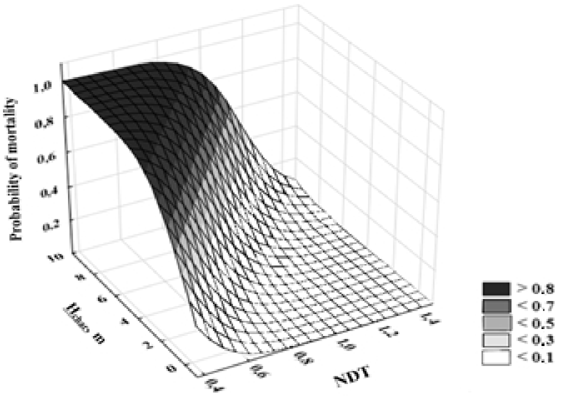

Fig. 2. Probability of postfire mortality in middle-aged pine stands depending on the height of bark char and the natural degree of thickness (NDT). The accuracy of the prediction model reaches 78.2%. The high quality of the proposed model was confirmed by ROC analysis (AUC = 0.83 ± 0.020). The inclusion of more variables in the model did not increase its accuracy by more than 1%. According to the sanitary condition classification, the dead trees belonged to the fifth and sixth categories of the sanitary condition. "The dying trees" susceptible to stem tree beetles (category IV of sanitary state) that will probably die with time have not been taken into account, so the cut-off limit for the above model has been reduced to 0.38.

The one-way ANOVA analysis confirmed the significance of fire damage of thin (light) bark. Trees with average NDT ranging from 0.9 to 1.1, same age and in bark char height on the trunks (2.8–3.1 m), were selected for analysis. The sample was divided into three groups: "rough bark" – when the bark char did not exceed the height of the rough bark; "transition zone" – when the bark char reached one meter below the zone of transition to thin bark or reached the zone of transition of the coarse bark; and the third group, "thin (light) bark damage" – the height of bark char exceeded the zone of transition of the rough bark to the thin one. The effect of thin bark area damage on the trees´ sanitary state was statistically significant (Ff = 5.98; Fst = 3.07; (p = 0.003) (Fig. 3, Fig. 4).

Thus, selecting drying-prone trees for cutting (as trees that are likely to die), it is worth paying attention to the presence of thin bark burns. In cases where the height of the bark char height exceeds the height of the coarse bark (thin bark fire damage), the likelihood of postfire trees mortality increases dramatically.

Fig. 3. Transition zone: rough bark goes into thin light color bark.

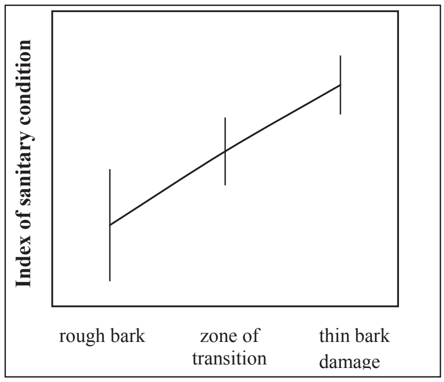

Fig. 4. Index of sanitary condition for groups of trees which have equal height of bark char.

3.3. Postfire tree mortality in the mature pine stands

It was found that in mature pine stands there is no significant relationship between bark char height and the trees´ sanitary state. Taking into account the role of the char height on the trunks as an indicator of fire damage, tables of predicted mortality were drawn up separately for summer and spring fires (Table 5).

Table 5. Sanitary state and postfire mortality in mature pine stands damaged by surface fires.

H_{char} [m]	Season of fire					
	Spring			Summer		
	I_s	Proportion of dead trees [%]		I_s	Proportion of dead trees [%]	
		N	M		N	M
0–0.5	2.7	5.9	2.6	4.3	33.0	38.4
0.5–1.0	3.0	7.4	3.2	4.5	54.0	55.9
1.1–1.5	2.9	5.4	1.7	4.1	56.0	65.6
1.5–2.0	2.9	5.4	3.5	4.3	31.0	27.0
2.1–2.5	2.9	1.5	1.2	4.7	64.0	52.3
2.6–3.0	2.9	4.8	3.4	4.7	64.0	72.1
3.1–4.0	2.7	3.0	4.2	5.7	83.0	72.3

Note: *Is* – index of sanitary state; H_{char} – bark char height, %; N – number of trees, %; M – the share of the stock, %.

It was found that the damage caused by the spring fires did not pose a threat – the proportion of dead trees in the total stand stock did not exceed 3.4%. This indicates that the least developed trees die after the spring fires.

After the summer fires, the trees affected by any damage responded with rapid deterioration of their sanitary state. No significant relationship was found between the sanitary state of trees and damage value, although there is a tendency toward an increase in the proportion of dead trees as the average height of bark char increases (from 31 to 83% by the number of trees and from 27 to 72.3% by the stock). The proportion of dead trees by the number was inferior to the share of dead trees by the stock. This indicates that after the summer surface fires, the most developed dominant and predominant trees have a higher probability of mortality.

The suppressed small trees in the pine stand died at any level of damage (natural thinning by suppression) (Table 6). At the same time, the most developed trees of the highest natural degree of thickness (NDT) also responded to the damage most radically – the mortality rate was 48–55% even with minimal damage (the height of bark char up to one meter) and 100% for the bark char above one meter.

Trees whose DBH was inferior to the average in the stand, namely with a natural degree of thickness 0.7–0.8, were found to be the most fire resistant. The mortality rate in this group is minimal (0–5%). Thus, the diameter of mature and overmature pine trees is not an indicator of fire resistance: the slightly less developed and thinner trees have proved more resistant.

Table 6. Proportion of dead trees in mature pine stands, depending on the natural degrees of thickness (NDT) and bark char height (H_{char}) after summer smoldering fires, %.

Bark char height (H_{char}) [m]	Natural degrees of thickness				
	>0.6	0.7–0.8	0.9–1.0	1.1–1.2	1.3–1.4
>1.0	43	5	48	54	55
1.1–2.0	—	0	69	100	100
2.1–3.0	—	0	100	100	100
3.1–4.0	—	0	100	100	100

A tendency was established toward an increase in the share of dead trees with an increase in their diameter. Correlation analysis established a strong direct reliable relationship ($t_f = 5.84$; $t_{0.01} = 3.71$) between these indicators. One of the reasons for the higher mortality of large-sized trees was the bigger amount of litter accumulated near tree basis. Thus, in the undamaged parts of the pine stands measurements were taken of the thickness of the litter and duff at different distances from the trunk.

The thickness of litter and duff layers near the tree basis varied within 7 to 14 cm (average value –11.0 ± 0.52 cm) and decreased as the distance from the trunk increased to 2.6 ± 0.30 cm, which is statistically confirmed ($F_f = 56,8$; $F_{0,001} = 2.7$). Rough bark reaches only the level of the litter, therefore surface fires severely damage the cambium, leading to the weakening of the tree and ultimately to dying. It was found that the thickness of the bark on the pine root paws can be 2.5 times smaller than on the trunk above – 8.8 ± 0.99 mm versus 22.2 ± 2.29 mm. The reliability of the difference in bark thickness on model trees was statistically confirmed ($t_f = 5.54$; $t_{0.05} = 2.26$). The presence of open root paws, on the one hand, indicates damage to the first order roots, while on the other, is an indicator of a strong degree of forest litter combustion, which causes also damage to fine roots.

4. Discussion

Our results show that the response of pine trees of different age groups to the effect of surface fire differs greatly. In young pine stands, damage to the crown with simultaneous damage to the tree trunk prevails. In middle-aged pine trees prevails damage to the trunk; in mature pine stands – damage to the trunk by heat radiation and root systems (roots of the first order at the base of the tree). The deterioration of tree sanitary state or even the death of trees after the surface fire is caused by damage to stem tissues; buds and needles in the crown of the tree; damage to tree roots (Valendik et al. 2006; Kosov 2008), but the authors do not provide critical levels of damage for each age group of pine stands. The bark char indicator is widely used alone or in combination with crown scorch to predict postfire mortality of pine forests. These two indicators are considered to be the most significant ones (De Bano & Conrad 1978; McHugh & Kolb 2003). Kobechinskaya and Oturina (1997) indicated that the height of bark char is not necessarily the main criterion for the mortality in a stand. According to their research in the Crimea, the proportion of dead pine trees varies greatly, with the same height and different combustion and destruction of cambium. In our opinion, such variation is caused by differences in the stand and individual trees characteristics.

According to Dieterich (1979), the amount of damage to the crowns during fires has been identified as the main cause of coniferous tree mortality and has been successfully used to predict postfire mortality. In our opinion, crown scorch should be included in the prediction models of postfire tree mortality, especially for predicting mortality in young pine stands, where this type of damage is typical during surface fires and closely correlates with the deterioration of the sanitary state of damaged trees. The surface fires in the young pine stands are extremely dangerous. Because of the low height crown attachment, the fire causes severe damage to both tree trunks and tree crowns. Due to this, for young pine stands it is advisable to use also “relative bark char” (the ratio of maximum bark char height to the height of the tree) as an additional indicator. This criterion is not new and was used Regelbrugge and Conard (1993), but it is appropriate to use it for young pine stands. This technique allows to predict postfire mortality of trees more accurately, compared to using the “char height” indicator. According to our results, the lethal damage value of the crown scorch for young pine trees is 80% and relative bark char – 60%.

Critical for pine stands damaged during summer fires can be considered the average height of bark char above two meters, the sanitary index being 3.4 and the proportion of dead trees reaching 21%. As the average bark char height increased, so did the proportion of dead trees from 21% for bark char height of 1.5–2 m to 70% for bark char of more than 5 m the sanitary index ranging from 2.6 to 2.8. The rate of postfire tree mortality was insignificant (1–6%). The probability of postfire mortality of individual middle-aged trees after summer surface fires is determined depending on the diameter (DBH) of the trees and the value of damage to the trunk. Trees of the lowest natural degree of thickness (NDT 0.6–0.7) are killed by minor damage to the trunk (up to 1 m). The risk of postfire mortality for trees with the NDT of 1.0–1.1 is significant only when the height of bark char is more than 3.5 m.

As is evidenced in major research papers (De Bano & Conrad 1978; Pinard & Huffman 1997; Stephens & Finney 2002), tree mortality rate is inversely related to the diameter of the trees, since larger trees typically have a thicker bark, which is a good insulator. According to our research, the height of the coarse bark may be an additional indicator of fire resistance of trees, especially for middle-age trees. The trees whose height of the bark char reaches the zone of the thin bark (its thickness being 0.1–0.9 mm), respond to damage by deterioration of the sanitary state and have a higher probability of mortality.

The thermal insulation properties of the bark layer depend on its thickness, structure, bulk density and humidity. These bark characteristics vary widely across tree species. The bark of coniferous tree species from family *Pinaceae* (*Pinus sylvestris* L., *Pinus pallasiana* D. and others) is the most successfully adapted for the thermal isolation of living tissues from fire damage (Valendik et al. 2006). Some authors (Hare 1965) provide data about fire resistance, which is related to morphological features and increases with the size of the tree (diameter) and its age. Other authors have reported that the diameter and thickness of the bark are poorly correlated with the postfire mortality rate (Menges & Deyrup 2001). Basically, the conclusions are often contradictory. On the other hand, authors of similar works (Hood et al. 2007) claim that trees with a larger diameter, on the contrary, are less resistant to fires. In our research, such conclusions are only partially confirmed. In mature pine trees, especially after the summer fires and smoldering fires, the fire resistance of the most developed trees was negligible, they died after exposure to even minimal fire damage. Tree mortality may take place in case of the small thickness of the bark and its high thermal conductivity in trees with smaller diameter (DBH) (Kosov et al. 2005), so young and middle-aged pine trees larger in size proved more fire-resistant and had a better sanitary state one year after fire. In our opinion, the authors came to different conclusions because they did not take into account the fire intensity, damage to the roots and tree morphological changes relative to its age. Our results have shown that the high rate of mortality and probability of mortality of more developed large trees in mature pine stands is associated with the accumulation of a relatively larger stock of litter and duff at the tree base near the trunks. This contributes to the increased intensity of fire and its localization near the tree trunk. The bark on the root paws (8.8 ± 0.99 mm) in mature pines is 2.5 times thinner than on the trunk 10 cm above ground (22.2 ± 2.29 mm). Therefore, summer surface fires damage the cambium in this location, which leads to the weakening of the trees and their subsequent dying. According to Fowler and Cieg (2004), damage to fine roots can be crucial for their postfire survival. Prolonged heat during smoldering fires can cause root damage when first order roots near the base of the trunk are damaged and die off. Along with them, the rest of the higher order roots, which are related to the first order roots, will also die (Guo et al. 2008). J. Varner (2009) demonstrates that the lethal temperature during a fire, spreads deeper than 20 cm into the soil. O'Brien found (O'Brien et al. 2010), that the fine roots of *Pinus palustris* Miller were almost evenly distributed in the lower layers of forest duff and developed in the upper 30 cm of soil. Although the thermal conductivity of the soil is negligible, the fire can, in certain conditions, significantly damage the root systems. Therefore, if the trees in the pine stand form a surface root system, a smoldering fire can significantly affect the root systems. At the same time, a steady smoldering fire that damaged the cambium near the root (tree basis zone) can cause a long-term weakening of the trees, reduce resistance to beetles´ attacks and lead to the death of the pine stand. Similar processes were recorded by Varner (2009) in mature pine trees that were damaged during smoldering fire in the summer; such trees died even with slight damage (up to 0.5 m of bark char height). Varner, in his work, came to the same conclusion, finding that in low intensity surface fires, mature pine trees can withstand fire damage, but a smoldering fire in planting with a thick layer of litter and duff can cause more than 80% of trees to die (Thies et al. 2006; Varner et al. 2009).

The intensity of postfire mortality depends also on the season of fire (spring, summer, autumn). This phenomenon was not clear due to a number of reasons. For example, Menges and Deyrup (2001) argue that the intensity of post fire mortality is the highest after the autumn and winter fires. Harrington (1987) claimed that more intense postfire mortality occurred during spring fires (active season) than after autumn ones (dry season), while Thies (2005), on the other hand, determined greater tree mortality after fall than after spring. It is logical to assume that the season itself, as a factor, has little effect on tree mortality, the main role being played by the intensity and characteristic of the damage. That is, in the summer, the intensity of the fire is greater, especially during prolonged droughts when forest fuel dries up to a critical level. This hypothesis has been confirmed in the research of Thies (2006). Our results have shown that summer fires have a more negative impact on pine stands. Summer fires for middle-aged, mature and overmature pine stands have more significant consequences than spring fires. The intensity of postfire tree mortality after summer surface fires in mature pine trees was 10 times higher than after spring fires. Since spring fires are rapid, only the top thin layer of litter is burned during the fire, and the wetter ones do not burn out. Such type of damage is less significant than in summer, all the litter and duff burning, and damage to the trunk is also accompanied by damage to the root and the destruction of the most physiologically active fine roots in the topsoil. In addition, trees damaged in early spring do not experience lack of moisture, and they recover faster after being damaged.

5. Conclusions

We conclude that fire resistance patterns in pine trees change during their growth and vary greatly between different age groups. We have found evidence that in young, middle-aged and premature pine stands the main indicators of fire resistance are connected to the tree size – large trees appear more resistant. The main indicators of fire resistance were thus tree diameter, tree height, NDT, Kraft class, and other related indicators. In mature stands, on the contrary, larger trees were less resistant to fire damage. The reason is that trees with larger diameter in mature pines stands accumulate a relatively larger stock of fuel (litter and duff) near the tree trunks. This contributes to the local increase of fire intensity and its localization near the tree trunk. Such local changes in fire behavior lead to severe damage to the lower part of tree trunks and the death of damaged trees. The height of the coarse bark may be an additional indicator of pine tree fire resistance. Trees whose height of the bark char does not exceed the zone of the coarse bark have a better sanitary condition and a higher probability of survival.

References

Ahafonov, A. F., Alekseev, Y. A., 1989: Drying of pure pine on fires. Forestry, 12:37–39.

De Bano, L. F., Conrad, C. E., 1978: The effect of fire on nutrients in a chaparral ecosystem. Ecology, 59:89–97.

Dieterich, J. H., 1979: Recovery potential of fire-damaged southwestern ponderosa pine. USDA Forest Service – Rocky Mountain Forest and Range Experiment Station Research Note RM-379. Ft. Collins, Colorado, 8 p.

Eichhorn, J., Roskams, P., Ferretti, M., Mues, V., Szepesi, A., Durrant, D., 2010: Visual assessment of crown condition and damaging agents. Manual Part IV. In: Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests – UNECE-ICP Forests Programme Co-ordinating Centre, Hamburg, 49 p.

Fawcett, T., 2004: ROC Graphs: Notes and Practical Considerations for Researchers. Kluwer Academic Publishers, 38 p.

Fites-Kaufman, J. A., Weixelman, D., Merrill, A. G., 2008: One-Year Postfire Mortality of Large Trees in Low- and Moderate-Severity Portions of the Star Fire in the Sierra Nevada 1. Session K – Postfire Mortality of Large Trees in Sierra Nevada. USDA Forest Service General Technical Reports PSW-GTR-189:279–284.

Fowler, J. F., Sieg Fowler, C. H., 2004: Postfire mortality of ponderosa pine and Douglas-fir: a review of methods to predict tree death. Gen. Tech. Rep. RMRS-GTR-132. USDA Forest Service, Fort Collins, Rocky Mountain Research Station, 25 p.

Guo, D. L., Mitchell, R. J., Withington, J. M., Fan, P. P., Hendricks, J. J., 2008: Endogenous and exogenous controls of root lifespan, mortality and nitrogen flux in a longleaf pine forest: root branch order predominates. Journal of Ecology, 96:737–745.

Hare, R. C., 1965: The contribution of bark to fire resistance of southern trees. Journal of Forestry, 4:248–251.

Harrington, M. G., 1987: Ponderosa pine mortality from spring, summer, and fall crown scorching. Journal of Applied Forestry, 2:14–16.

Hood, S. M., Smith, S. L., Cluck, D. R., 2007: Delayed conifer tree mortality following fire in California. USDA Forest Service Gen. Tech. Rep. PSW-GTR-203. USA, Albany, Calif., 261–283 p.

Kobechinskaya, V. G., Oturina, I. P., 1997: Ecological consequences of the impact of fires on the vegetation cover of mountain Crimea. Issues of bioindication and ecology of Zaporozhye, 2:28–31.

Kosov, I. V., 2008: The mechanism of the impact of grassroots fires on trees of coniferous species. Fires in Siberia's Forest Ecosystems – Vseros Materials. Conf. with international. participation, 17–19 September, 2008, Krasnoyarsk, p. 146–149.

Kosov, I. V., Kisilyahov, E. K., Rybnikov, V. Yu., 2005: The mechanism of damage to the stand during litter-humus fires. Nerd. researched in Siberia, Krasnoyarsk, 13:97–101.

Lakyn, H. F., 1990: Biometrics. 4th, rework. Moscow, Vyshcha shkola, 352 p.

Mashkovsky, V. P., 2015: Commoditization of the rated cutting by assortment tables with tree row distribution according to natural diameter classes. Problems of Forest and Forestry: collection of scientific works of Institute of Wood of NAS of Belarus, 75:340–348 p.

Mason, W. L., Alìa, R., 2000: Investigación agraria. Sistemas y recursos forestales, 9:3–17.

McHugh, C. W., Kolb, T. E., 2003: Ponderosa pine mortality following fire in northern Arizona. International Journal of Wildland Fire, 12:7–22.

Menges, E. S., Deyrup, M. A., 2001: Postfire survival in south Florida slash pine: interacting effects of fire intensity, fire season, vegetation, burn size, and bark beetles. International Journal of Wildland Fire, 10:53–63.

O'Brien, J. J., Hiers, J. K., Mitchell, R. J., Morgan Varner III, J., Mordecai, K., 2010: Acute physiological stress and mortality following fire in a long-unburned longleaf pine ecosystem. Fire Ecology, 6:1–12.

Pinard, M. A., Huffman, J., 1997: Fire resistance and bark properties of trees in a seasonally dry forest in eastern Bolivia. Journal of Tropical Ecology, 13:727–740.

Pogrebnyak, P. S., 1968: General forestry. Moscow, Kolos, 440 p.

Regelbrugge, J. C., Conard, S. G., 1993: Modeling tree mortality following wildfire in *Pinus ponderosa* forests in the central Sierra Nevada of California. International Journal of Wildland Fire, 3:139–148.

Sah, J., Ross, M., Ogarcak, D., Snyder, J., 2006: Fuel Loads, Fire Severity, and Tree Mortality in Florida Keys Pine Forests. International Journal of Wildland Fire, 15:463–478.

San-Miguel-Ayanz, J., Durrant, T., Boca, R., Libertà, G., Branco, A., de Rigo, D., Ferrari, D.et al., 2017: Forest Fires in Europe, Middle East and North Africa, 142 p.

State Forest Resources Agency of Ukraine, 2017: Forests and forestry in Ukraine. Sci. Bull. UNFU, 27: 10–15.

Stephens, S. L., Finney, M. A., 2002: Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion. Ecology and Management, 162:261–271.

Svyrydenko, V. Ye., Babich, O. H., Kyrychok, L. S. 2004: Forestry. Textbook. Kyiv, Aristey, 544 p.

Thies, W. G., Westlind, D. J., Loewen, M., 2005: Season of prescribed burn in ponderosa pine forests in eastern Oregon: impact on pine mortality. International Journal of Wildland Fire, 14:223–231.

Thies, W. G., Westlind, D. J., Loewen, M., Brenner, G., 2006: Prediction of delayed mortality of fire-damaged ponderosa pine following prescribed fires in eastern Oregon, USA. International Journal of Wildland Fire, 15:19–29.

Tyurin, A. V., 1945: Forest mensuration. Moscow, Goslestekhizdat, 376 p.

Usenya, V. V., Churylo, V. S., 2001: The dynamics of post-fire mortality in pine stands. Problems of Forest and Forestry: collection of scientific works of Institute of Wood of NAS of Belarus, 52:209–214.

Valendik, E. N., Suhinin, A. I., Kosov, I. V. 2006: Effect of forest fires on the stability of conifers Krasnoyarsk. Krasnoyarsk, Scientific Center of the Siberian Branch of the RAS, 96 p.

Varner, J. M., Putz, F. E., O'Brien, J. J., Hiers, J. K., Mitchell, R. J., Gordon, D. R., 2009: Post-fire tree stress and growth following smoldering duff fires. Forest Ecology and Management, 258:2467–2474.

Voron, V. P., Melnyk, Ye. Ye., 2009: Tendencies of fires development in the forests of green belt of Kharkov. Forestry and Forest Melioration, 115:207–214.

Internet sources:

FAO, 2006: Fire management: Review of international cooperation. Fire Management Working Paper FM18E. Available at: https://www.fao.org/3/j9406e/j9406e00.

Sanitary Forests Regulations in Ukraine, 2016: Approved by Cabinet of Ministers of Ukraine. Kyiv, 20 p. Available at: https://zakon.rada.gov.ua/laws/show/555-95-%D0%BF#Text.

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Habitat selection of semi-free ranging European bison: Do bison preferred natural open habitats?

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Abstract

European bison (*Bison bonasus*) were successfully reintroduced in many free or semi-free areas across Europe during the last decades. Due to the increased numbers, the conflicts between human activities and bison are more frequent. Therefore the knowledge about spatial activity and habitat preference in new regions is the need for management decision making. We studied daily and seasonal habitat use of the semi-free European bison herd in the Czech Republic from 2014 to 2019. The lead cows of the herd were collared with the GPS devices with a 30-minutes GPS fixes interval. The bison herd strongly preferred the managed open areas and supplementary feeding stations during the seasons (Jacob´s index from 0.49 to 0.99). On the contrary, they avoided the forest type and unmanaged open habitats (Jacob´s index from −0.23 to −0.69). The managed meadows and feeding places they used almost exclusively during the night while the forest during the day-light.

Key words: habitat preference; Jacob´s index; forest, open areas; feeding station

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1. Introduction

The European bison is the largest wild ungulate on the European continent (Ramos et al. 2016). At the end of the 19th century, it was on the verge of extinction, but thanks to a successful reintroduction programme, more than 40 wild yet geographically separated populations currently live in Europe (Raczynski 2019). Due to the fact that the European bison is introduced to new areas and different types of environments, there is still a lack of a unified view of its habitat preferences and what its natural environment is. The European bison is considered a species that prefers a forest environment (Plumb et al. 2009; Bleier et al. 2012; Hofman-Kamińska & Kowalczyk 2012). However, the reason may be that the European bison is an example of a species that has been forced to move into the forest due to a combination of overgrowth of open areas after the last postglacial period and increasing human pressure on it (Cromssigt et al. 2012; Kerley et al. 2012). Based on these assumptions and the fact that the European bison needs a large amount of herbaceous vegetation each day, in recent years the bison has been very often introduced to places where it should serve as one of the species naturally farming open grassy and bushy succession habitats. In these types of vegetation, the European bison should prevent the spread and development of shrubs and trees and thus maintain these areas (Jirků & Dostál 2020). The presence of the European bison in these semi-wild farms has a significant effect on the species structure of habitats (Dostál et al. 2012). This is often the reason for the so-called rewilding concept, which assumes the reintroduction of species that have disappeared from the landscape or species farmed with the aim of increasing biodiversity without the need for active human management. This idea also often includes the reintroduction of the European bison in many areas of Central and Eastern Europe, namely Germany, Poland, Lithuania and Latvia. Where several highly suitable regions large enough to support a new herd were found, with the optimal areas being in Poland, the European bison was introduced in this way (Lord et al. 2020). Usually, semi-wild breeding is significantly limited (fenced) in space, however, with the ambition of spreading the European bison into the wild. And as like in the case of open landscape, habitat preferences may be different. This can be reflected in the resulting impact on different types of habitats. Therefore, we decided to evaluate the habitat preferences of European bison herds bred in semi-wild breeding in the Czech Republic.

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2. Material and methods

2.1. Study area

Židlov is a nature reserve with an approximate area of 38 km^2 and is one of the largest fields in Central Europe. It is located in the northern part of the Czech Republic and was established in 2000 on the territory of a former military training ground. 55% of the area is occupied by commercial forests, of which 88% are conifers (pine, spruce) and 12% deciduous trees (birch, oak). The rest of the area (38%) consists of former impact areas that have been left to natural succession and currently form a forest-steppe landscape with a predominance of unmaintained grasses, pioneer trees and shrubs. Cultivated agricultural land occupies 5% and consists of maintained meadows used for grazing game. In the nature reserve there are red deer, fallow deer, mouflon, roe deer, and wild boar. Since 2011, European bison, which have been imported from Białowieża Forest and Kampinos National Park, have been bred in the nature reserve. Currently, there is a herd of a total of 34 European bison in the nature reserve (Raczyński 2019). Since 2014, wolves that are able to overcome fencing occasionally occur in the nature reserve.

2.2. Data collection

Between 2014 and 2018, the movement of the European bison herd was monitored with a telemetry collar (VECTRONIC Aerospace GmbH; type GPS Plus 5D). The sampling frequency of GPS positions was 30 minutes (Červený et al. 2014). GPS data were used according to the method of Lewis et al. (2007), and all positions with DOP less than 6 were not used in the analyzes due to high inaccuracy of measurement. A total of 23,000 positions were available.

Information about the environment comes from the mapping itself, when on the basis of field walks the area was vectorized and habitats were divided into the following main types: Meadow, Bush, Forest, Feeding places. Meadow is a grassland economically maintained and restored, which is used to graze game kept in the nature reserve. Bush is formed by stands of early successional stages, which are gradually overgrown with shrubs and trees; these stands are not maintained. Forests are commercial forests used for wood production. Feeding places are places where supplementary feed (grain, corn, hay, haylage) is presented to game throughout the year. An area with a radius of 100 meters from the feeding facility was defined as a feeding place.

2.3. Statistical analyses

Occurrence and habitat data were processed in ArcGIS 10.7 software (ESRI 2010). The spatial join tool was used to link bison herd data and habitat type.

The Jacob's index was used to determine habitat preferences. The Jacob's index was calculated according to the formula:

$$D = (r - p)/(r + p - 2rp),$$

where r is the proportion of habitat used and p the proportion of habitat available. D varies from −1 (strong avoidance) to +1 (strong preference), and values close to zero indicate that the habitat is used in proportion to its availability (Jacobs 1974; Kauhala and Aittilla 2008).

Data normality was tested using the one-sample Kolmogorov-Smirnov test. If the distribution was not normal, a nonparametric test was used to compare the data. For the Jacob's index, 95% confidence intervals were calculated to find the difference in different parts of the year.

The data were divided according to the time distribution in the year, either according to calendar months or seasonality for spring (March, April, May), summer (June, July, August), autumn (September, October, November) and winter (December, January, February).

The Oriana 4.02 software (Kovach Computing) and circular statistics were used to examine the distribution of habitat preference during the 24-hour cycle (Lehner 1996). Significant deviations from random distributions were investigated using the Rayleigh test of circular statistics.

3. Results

On average across the entire time period, the European bison herd used forest type (34%), feeding places (23%), meadow (22%) and bush (21%). However, habitat use varied significantly between seasons (Kruskal-Wallis Anova, $p < 0.000$; Fig. 1). Forest stands were mostly used by bison in summer (47%) and least in autumn (20%), feeding places mostly in winter (58%) and least in summer (3%), meadows mostly in summer (33%) and least in winter (5%), and bush most in summer (23%) and least in winter (15%).

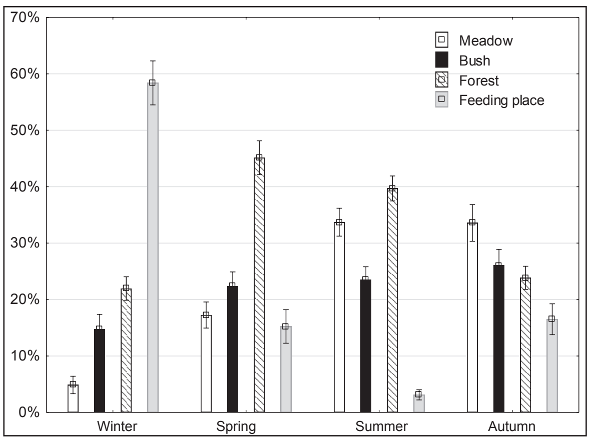

Fig. 1. Habitat utilization of bison during the seasons (% of total location in the season) for different type of habitat (column = mean; whisker = mean ± 0.95 conf. interval).

As for the preferences in individual seasons (Fig. 2 and Table 1), the largest Jacob's index showed a bison herd for feeding places in winter (0.98), spring (0.87), autumn (0.86), only in summer the preference slightly decreased (to 0.41). Another type of vegetation that European bison strongly preferred were cultivated meadows. In spring the Jacob's index was 0.49, in summer 0.76, in autumn 0.70. Only in winter the index fell to −0.14. On the contrary, the European bison did not prefer, or even deliberately avoided the forest and bush. The Jacob's index for the forest ranged from −0.69 in the fall to −0.23 in the spring. It was similar for bush, when the index took values from −0.49 in winter to −0.26 in spring.

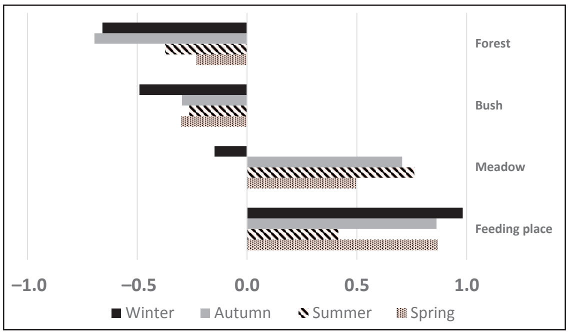

Fig. 2. Habitat preference of bison during the seasons (Jacob´s index) for different type of habitat.

Table 1. Values of Jacob´s index for month´s and different type of habitat.

	Feeding place	Meadow	Bush	Forest
January	0.99	−0.42	−0.71	−0.67
February	0.96	−0.11	−0.23	−0.53
March	0.96	0.36	−0.36	−0.49
April	0.77	0.53	−0.28	−0.15
May	0.00	0.57	−0.27	−0.05
June	0.56	0.73	−0.22	−0.34
July	-0.01	0.79	−0.31	−0.33
August	0.48	0.78	−0.24	−0.41
September	0.78	0.79	−0.21	−0.55
October	0.86	0.77	−0.17	−0.61
November	0.94	0.72	−0.19	−0.73
December	0.99	0.02	−0.52	−0.75

The distribution of habitat use also shows statistically significant differences (Table 2). In winter, when the differences in preference according to the Jacob's index are greatest, European bison primarily use feeding places and meadows during the night, while forest almost exclusively during the day. Bush, on the other hand, is used during dawn (Fig. 3). At the same time, in meadows and forests there is a very high value of the mean length of the vector and the concentration of data in the preferred parts of the day throughout the year. With the exception of spring, the values of bushes are very low and the significance is also an order of magnitude lower than for other types of stands.

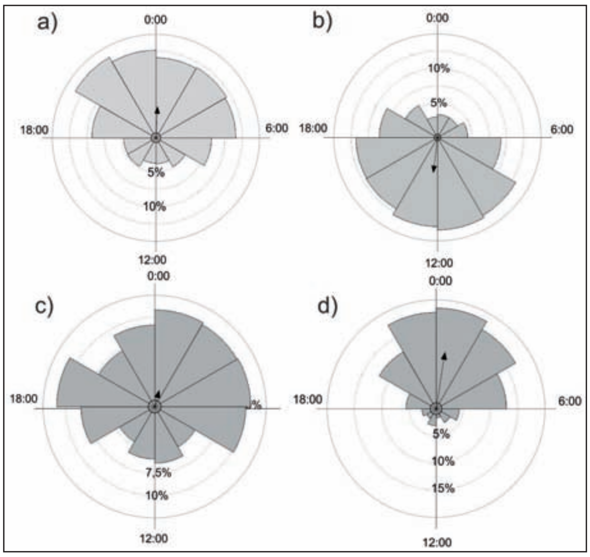

Fig. 3. Daily habitat selection during the spring: a) bush; b) forest; c) feeding place; d) meadow.

4. Discussion

The high preference of the forest corresponds to the results found in other studies. As reported by Bleier et al. (2012) or Hofman-Kamińska and Kowalczyk (2012), the European bison prefer forest type environments, especially during daytime (Červený et al. 2014; Marozas et al. 2019). Conversely, at night, European bison prefer open stands (Pucek et al. 2004; Daleszczyk et al. 2007; Marozas et al. 2019). This corresponds to the theory that bison changed their behaviour after the last postglacial period,

Table 2. Circular statistics values for daily use of different type of habitat and season.

		Spring	Summer	Autumn	Winter
Feeding place	Mean vector (time)	01:00	21:33	12:23	00:08
	Length of Mean Vector (r)	0.151	0.21	0.139	0.164
	Concentration	0.305	0.429	0.28	0.333
	Rayleigh Test (p)	< 0.001	< 0.001	< 0.001	< 0.001
Meadow	Mean vector	00:35	0:58	00:22	02:33
	Length of Mean Vector (r)	0.5423	0.486	0.412	0.200
	Concentration	1.222	1.109	0.904	0.409
	Rayleigh Test (p)	< 0.001	< 0.001	< 0.001	< 0.001
Forest	Mean vector	12:27	12:42	12:06	12:04
	Length of Mean Vector (r)	0.338	0.459	0.509	0.464
	Concentration	0.719	1.033	1.179	1.046
	Rayleigh Test (p)	< 0.001	< 0.001	< 0.001	< 0.001
Bush	Mean vector	00:11	00:06	20:37	19:14
	Length of Mean Vector (r)	0.299	0.099	0.035	0.092
	Concentration	0.628	0.199	0.069	0.184
	Rayleigh Test (p)	< 0.001	< 0.01	< 0.01	< 0.01

which was associated with a decrease in open areas and increasing activity of people for whom European bison were prey (Cromssigt et al. 2012; Kerley et al. 2012). Their frequent stay in open areas during the night can also be the result of better grazing, when, like other ruminants, they look for richer food habitats at a time when they are less disturbed by humans (Whittaker & Knight 1998). This is also confirmed by conclusions about the type of habitat preference. In most cases within our study these were maintained grasslands, regularly managed. Their share in the total area is only 5%, but bison occur in it up to 33% of the total time of day (Summer). Other natural successive shrub formations (Bush) are avoided throughout the year, even though they make up more than 43% of the total area. On average, they spend only 21% of their total time on them. In other studies, European bison similarly preferred cultivated farmland. E.g. in Lithuania (Marozas et al. 2019), European bison spent up to 56% of their time at night there, of which only 7% on the uncultivated land to which we can compare bush. On the contrary, they significantly preferred qualitatively rich types of vegetation, such as rape or cereals. European bison living on the borders of the Białowieża National Park showed similar preferences, when their home districts intervened in the agricultural landscape. This also supports the findings of Mendoza and Palmquist (2008), who rank the bison morphologically among the species adapted to live in rich grass communities. On the contrary, the results of food analyses carried out in the central part of the Białowieża National Park, where neither feeding is carried out nor cultivated agricultural crops are present, suggest that European bison prefer highly nutritious and easily digestible parts of woody plants, shrubs and herbs to grasses (Kowalczyk et al. 2019). At the same time, they also point out that the content of graminoids (which contain a large percentage of grasses) was higher, especially in the period when the supply of quality trees and shrubs was declining. This indicates a high degree of plasticity of the bison in food selection and they can thus be described as a generalist (Freeland 1991), where this type of animal prefers high quality food and is only selective if its presence in the environment is high.

The theory of the European bison as a generalist is also supported by the high intensity of the use of feeding places, which in our study achieved very high preferences (Winter Jacob's index = 1), and where the bison spent up to 60% of the day in their immediate vicinity (< 100 m).

Such a high preference for feeding sites can cause a significant reduction in flight distance and also to attraction by strengthening an animal's behavior through positive reinforcement and encouraging movement towards a stimulus (Haidt et al. 2018). Bisons aggregation by feeding sites may facilitate transmission of nematode *Ashworthius sidemi*, which occurs by ingesting an invasive larval stage (Radwan et al. 2010; Vadlejch et al. 2017).

5. Conclusion

We conclude that bison highly preferred the managed open habitats (meadows) and feeding sites all year around. The forest habitats bison use usually during the daylight which is related to antipredation behavior. In contrary they avoid the opened unmanaged succession areas. This can cause conflicts between the humans and bison interests. It´s also necessary to consider the relationship with other game species because of the high preference for feeding stations by bison. This can cause that other species will have limited access to these places.

In the case of bison reintroduction in areas with intensively cultivated agricultural areas, it is appropriate to cultivate a special pasture areas for it and thus eliminate possible migration outside the core area and prevent damages and conflicts. A very common goal of bison reintroduction is to eliminate woody plants and other aggressive species of plant on the open succession areas by bison grazing. However, this purpose proves to be unsuitable for large semi free areas or in the free-range areas. It is suitable to implement it only in small limited farms, where the bison has a limited choice of habitat and food sources. To establish the management plans and true decision making policy, a detailed study of habitat preferences is suitable, especially in areas newly inhabited by bison.

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References

Bleier, N., Lehoczki, N., Újváry, D., Szemethy, L., Csány, S., 2012: Relationships between wild ungulates density and crop damage in Hungary. Acta Theriologica, 57:351–359.

Cromsigt, J. P. G. M., Kerley, G. I. H., Kowalczyk, R., 2012: The difficulty of using species distribution modeling for the conservation of refugee species–the example of European bison. Diversity and Distributions, 18:1253–1257.

Červený, J., Ježek, M., Holá, M., Zikmund, M., Kušta, T., Hanzal, V., Kropil, R., 2014: Daily activity rhythm and habitat use of the semi-free European bison herd during the growing season. Lesnícky časopis – Forestry Journal, 60:199–204.

Daleszczyk, K., Krasińska, M., Krasiński, Z. A., Bunevich, A. N., 2007: Habitat structure, climatic factors, and habitat use by European bison (*Bison bonasus*) in Polish and Belarussian parts of the Białowiez˙a Forest, Poland. Canadian Journal of Zoology, 85: 261–272.

Dostál, D., Jirků, M., Konvička, M., Čížek, L., Šálek, M., 2012: Návrat zubra evropského (*Bison bonasus*) do České republiky. Česká krajina, Kutná Hora, 120 p.

Freeland, W. J., 1991: Plant secondary metabolites: biochemical coevolution with herbivores. Plant defenses against mammalian herbivory. CRC Press, Boca Raton, p. 61–81.

Haidt, A., Kamiński, T., Borowik, T., Kowalczyk, R., 2018: Human and the beast – Flight and aggressive responses of European bison to human disturbance. PLOS ONE, 13:e0200635.

Hofman-Kamińska, E., Kowalczyk, R., 2012: Farm Crops Depre-dation by European Bison (*Bison bonasus*) in the Vicinity of Forest Habitats in Northeastern Poland. Environmental Management, 50:530–541.

Jacobs, J., 1974:. Quantitative measurement of food selection. Oecologia, 14:413–417.

Jirků, M., Dostál, D., 2020: Zhodnocení managementu bezlesí VVP Milovice – Mladá přirozenou pastvou velkých kopytníků 2015 – 2019. Praha, 25 p.

Kauhala, K., Auttila, M., 2010: Estimating habitat selection of badgers-a test between different methods. Journal of Vertebrate Biology, 59:16–25.

Kerley, G. I. H., Kowalczyk, R., Cromsigt, J. P. G. M. 2012: Conservation implications of the refugee species concept and the European bison: king of the forest or refugee in a marginal habitat? Ecography, 35: 519–529

Kowalczyk, R., Wójcik, J. M., Taberlet, P., Kamiński, T., Miquel, Ch., Valentini, A. et al., 2019: Foraging plasticity allows a large herbivore to persist in a sheltering forest habitat: DNA metabarcoding diet analysis of the European bison. Forest Ecology and Management, 449:117474.

Lehner, P. N., 1996: Spatial orientation and time: circular statistics and spatial patterns. In: Lehner, P. N. (ed.): Handbook of ethological methods. Cambridge University Press, p. 485–521.

Lewis, J. S., Rachlow, J. L., Garton, E. O., Vierling, L. A., 2007: Effects of habitat on GPS collar performance: using data screening to reduce location error. Journal of Apply Ecology, 44:663–671.

Lord, C. M., Wirebach, K. P., Tompkins, J., Bradshaw-Wilson, C., Shaffer, Ch. L., 2020: Reintroduction of the European bison (*Bison bonasus*) in central-eastern Europe: a case study. International Journal of Geographical Information Science, 34:1628–1647.

Marozas, V., Kibiša, A., Brazaitis, G., Jõgiste, K., Šimkevičius, K., Bartkevičius, E., 2019: Distribution and Habitat Selection of Free-Ranging European Bison (*Bison bonasus* L.) in a Mosaic Landscape–A Lithuanian Case. Forests, 10:339–345.

Mendoza, M., Palmqvist, P., 2008: Hypsodonty in ungulates: an adaptation for grass consumption or for foraging in open habitat? Journal of Zoology, 274: 134–142.

Plumb, G. E., White, P. J., Coughenour, M. B., Wallen, R. L., 2009: Carrying capacity, migration, and dispersal in Yellowstone bison. Biologicall Conservation, 142: 2377–2387.

Pucek, Z., Belousova, I. P., Krasińska, M., Krasiński, Z. A., Olech, W., 2004: European bison. Status survey and conservation action plan. IUCN/SSC Bison Specialist Group. IUCN, Gland, Switzerland.

Raczyński, J., 2019: European bison pedigree book. Białowieski Park Narodowy, 100 p.

Radwan, J., Demiaszkiewicz, A. W., Kowalczyk, R., Lachowicz, J., Kawalko, A., Wojcik, J. M.et al., 2010: An evaluation of two potential risk factors, MHC diversity and host density, for infection by an invasive nematode *Ashworthius sidemi* in endangered European bison *(Bison bonasus)*. Biological Conservation, 143:2049–2053.

Ramos, A., Petit, O., Longour, P., Pascuarett, C., Sueur, S., 2015: Collective decision making during group movements in Europea bison *(Bison bonasus)*. Animal Behavior, 109:149–160.

Ramos, A., Petit, O., Longour, P., Pasquaretta, C., Sueur, C., 2016: Space use and movement patterns in a semi-free-ranging herd of European bison (*Bison bonasus*). PloS One, 11:e0147404.

Vadlejch, J., Kyriánová, I. A., Rylková, K., Zikmund, M., Langrová, I., 2017: Did European bison conservation program introduced an alien parasite to the Czech Republic? Biological Invasions, 19:1121–1125.

Whittaker, D., Knight, R. L., 1998: Understanding wildlife responses to humans. Wildlife Society Bulletin, 26:312–317.

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ORIGINAL PAPER

Effects of forest disturbance on seasonal soil temperature changes in the Tatra Mountains in southern Poland

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Abstract

The purpose of the study was to examine the effects of forest disturbance on seasonal changes in soil temperature in the Tatra Mountains (Poland). In the years 2015–2020 soil temperatures were measured at a depth of 20 cm on north- and south-facing mountain slopes in a catchment where forest was disturbed by hurricane-force winds in 2013 and in a control neighboring woodland catchment. The effect of forest disturbance was manifested first and foremost in an increase in the soil temperature during the summer months – average by 1.8 to 2.4 °C on a south-facing mountain slope – and by about 1 °C on a north-facing slope. The buffer effect of forest on soil temperature can be observed via lower coefficients of correlation between soil temperature and air temperature in a woodland catchment versus a disturbed catchment in the summer. In the winter, the effect of forest disturbance on soil temperature was less pronounced than in the summer. Small differences in soil temperature in the winter between the woodland catchment and the disturbed catchment were associated with the presence of snow cover and its capacity to yield thermal insulation. Good insulation of the soil from the atmosphere generated by snow cover yielded a very weak relationship between soil temperature and air temperature in the winter. In springtime the soil temperature increased the fastest on a south-facing slope in the disturbed catchment while in the autumn season, soil temperatures declined most rapidly on a slope facing north in the disturbed catchment.

Key words: soil temperature; forest disturbance; windthrow; seasonal changes; Tatra Mountains

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1. Introduction

The increase in air temperature observed across the Earth in the last few decades (Allen et al. 2018) is a cause of the rise in soil temperature. This pattern was examined in studies in the United States, where the soil temperature at most of nearly 300 stations has shown a trend of warming in the last 35 years, with the average warming rate at 0.38 °C per 10 years (Hu & Feng 2003). The increase in soil temperature and the associated soil drought have served as the cause of forest disturbance in many parts of the world over the last few decades (Allen et al. 2010; Anderegg et al. 2012; Martinez-Vilalta 2012; Steinkamp et al. 2015). Forest disturbance as well as deforestation drive an array of feedback mechanisms. For example, they generally lead to a continuous increase in the soil temperature primarily due to an increase in near-ground solar radiation (Anderegg et al. 2012). The rise in soil temperature due to forest disturbance and deforestation triggers changes in the functioning of ecosystems. Water circulation patterns in catchments change mostly due to an increase in evaporation and decline in transpiration during low flow periods (Likens et al. 1970; Jewett et al. 1995; Anderegg et al. 2012). However, according to Gholami (2013), Hlásny et al. (2015) and Khaleghi (2017), deforestation causes increase in peak discharge and runoff volume during rainfall events. Forest disturbance along with the soil warming leads to changes in carbon cycling (Davidson & Janssens 2006; Allen 2009), as does nutrient cycling (Anderegg et al. 2012) and soil respiration (Londo et al. 1999; Schlesinger & Andrews 2000; Ney et al. 2019).

Most studies indicate that forest disturbance and deforestation cause a marked rise in soil temperature during the summer months (Donnelly et al. 1991; Bhatti et al. 2000; Hu et al. 2003; Moroni et al. 2009) and minor changes in the winter months (Donnelly et al. 1991; Hashimoto & Suzuki 2004; Moroni et al. 2009). However, Whitson et al. (2005) measured distinctly higher soil temperatures at harvested sites than at forest sites during snowmelt. Iwahana et al. (2005) also argue that

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clear-cutting enhances ground thawing and the depth of the soil active layer in areas underlain by permafrost, for example in the eastern Russian region of Siberia. Snow cover also plays an important role in seasonal changes in soil temperature. The depth of snow together with snow thermal conductivity play a key role in snow thermal insulation, as noted by Iwahana et al. (2005), Mellander et al. (2005) and Hu et al. (2013). Work by Mellander et al. (2005) showed that the nature of tree stands determines the thickness of snow cover in a woodland area. For example, an open tree stand together with a low surface area covered by its canopy ultimately result in thicker layers of snow.

The purpose of the present study was to investigate the effect of forest disturbance triggered by natural causes – such as a hurricane-force wind – on seasonal changes in soil temperature in a mountain region where tree stands are dominated by spruce. An increase in soil temperature after forest disturbance was expected; however, the key questions were the following: (i) What was the magnitude of the increase? (ii) How does slope exposure affect this magnitude? These are important questions today, as forest disturbance may increase soil warming caused by global climate warming. Despite the availability of several global soil surface temperature databases based on satellite products, according to Cassardo et al. (2018), there is still a lack of observational data on soil temperature profiles, especially for the root layer zone.

Initial research work focused on a comparison of soil temperature in a catchment where forest was disturbed by hurricane-force winds in 2013 and soil temperature in a neighboring undisturbed woodland catchment. In the course of the research a unique opportunity presented itself. It became possible to directly examine the effects of forest disturbance on soil temperature in the same catchment. Spruce stands in a woodland catchment experienced an attack of the bark beetle in 2018. In the following year the stands were partly overturned by high winds.

2. Material and methods

2.1. Study area and meteorological conditions

The research study was conducted in two small sub-catchments: (1) disturbed catchment, and (2) control woodland catchment (Fig. 1). Both sub-catchments are located in the Kościeliski Potok catchment area in the Polish part of Western Tatra Mountains, which is protected as Tatra National Park. The woodland catchment, called the Kończysta Turnia, has a surface area of 14.1 ha, while the disturbed catchment, called Pośrednia Kopka, has a surface area of 14.4 ha. The woodland catchment is located at elevations ranging from a minimum of 968 to a maximum of 1,264 m. The disturbed catchment is found at elevations in the range from 940 m to 1,200 m. The mean gradient of the woodland catchment is 30.1°, and that of the disturbed catchment is 23.6° (Żelazny et al. 2018). Both catchments are fragmented by narrow, deep V–shaped valleys, and are formed of sedimentary rocks: limestone, sandstone, conglomerates. These parent material rocks are covered with Rendzic Leptosols (Skeletic) and Haplic Cambisols (Eutric) (Skiba et al.

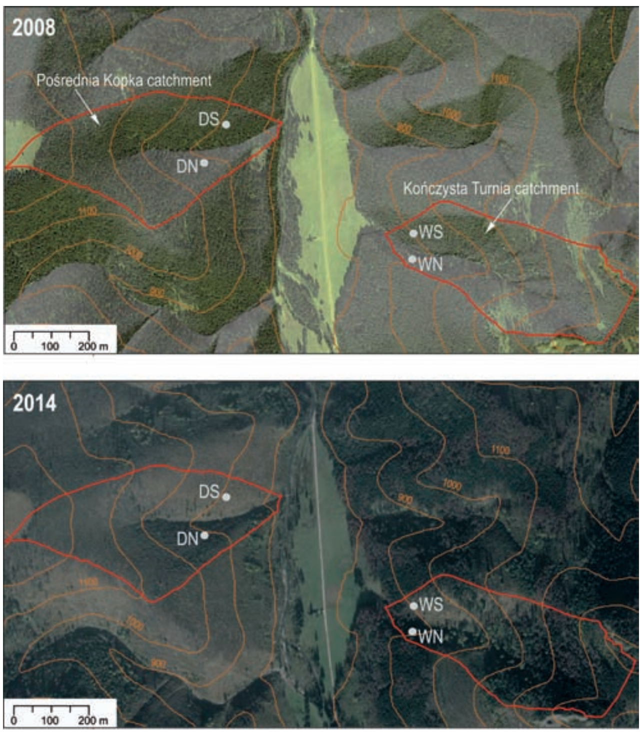

Fig. 1. Study area in 2008 and 2014.

2015). These soils are most often 40 to 60 cm deep. Soils found in the woodland catchment are characterized by the occurrence of horizon O (1–5 cm), while soils found in the disturbed catchment lack this horizon (Żelazny et al. 2018). In both catchments the mineral horizons are formed of silt loam (USDA classification); however, the A horizon is characterized by a higher proportion of sand than lower horizons (Table 1).

Table 1. Texture and carbon (C) content in mineral horizons of the soils in the studied disturbed and woodland catchments – data source: Żelazny et al. (2018).

Disturbed catchment							Woodland catchment						
Soil horizon	Depth [cm]	C	Sand	Silt	Clay	Texture*	Soil horizon	Depth [cm]	C	Sand	Silt	Clay	Texture*
		[%]							[%]				
A	0–4	6.89	24	64	12	Silt loam	A	0–6	6.66	29	60	11	Silt loam
AB	4–19	3.98	8	74	19	Silt loam	B	6–40	1.45	0	83	17	Silt loam
B_{Ca}	19–40	2.19	0	82	18	Silt loam	B_{Ca}	40–60	1.85	0	84	16	Silt loam

*according to United States Department of Agriculture.

The study area is located in a temperate climate zone – in a moderately cool climate zone (Hess 1965). According to Żmudzka et al. (2015) the mean annual air temperature ranges from 4 °C at lower elevations to 6 °C at high elevations. In the study period (2015–2020) the warmest months of the year were June, July, and August when the mean monthly air temperature exceeded 10 °C (Fig. 2a). The coolest months of the year when the mean monthly air temperature decreased below 0 °C were usually December, January, and February. The warmest winters in the study period occurred in late 2015 and early 2016 as well as late 2019 and early 2020 (Fig. 2a). According to Ustrnul et al. (2015), the mean annual atmospheric precipitation total in the study area ranges from 1,200 mm at lower elevations to 1,600 mm at high elevations. In the study period the highest atmospheric precipitation totals were recorded in the summer months (Fig. 2b). Snow cover appeared usually in October or November and melted in April or May. The largest snow depth was noted usually in December, January, and February, reaching usually more than 20 cm. Exceptionally small snow cover depths were noted in the winter of 2015/2016 (Fig. 2c).

Originally, the study area was occupied by Dentario glandulosae-Fagetum, dominated by beech (*Fagus sylvatica* L.), fir (*Abies alba* L.), and spruce (*Picea abies* L.). The trees were felled at the end of the 19th century and monocultures of spruce were planted at the begin-

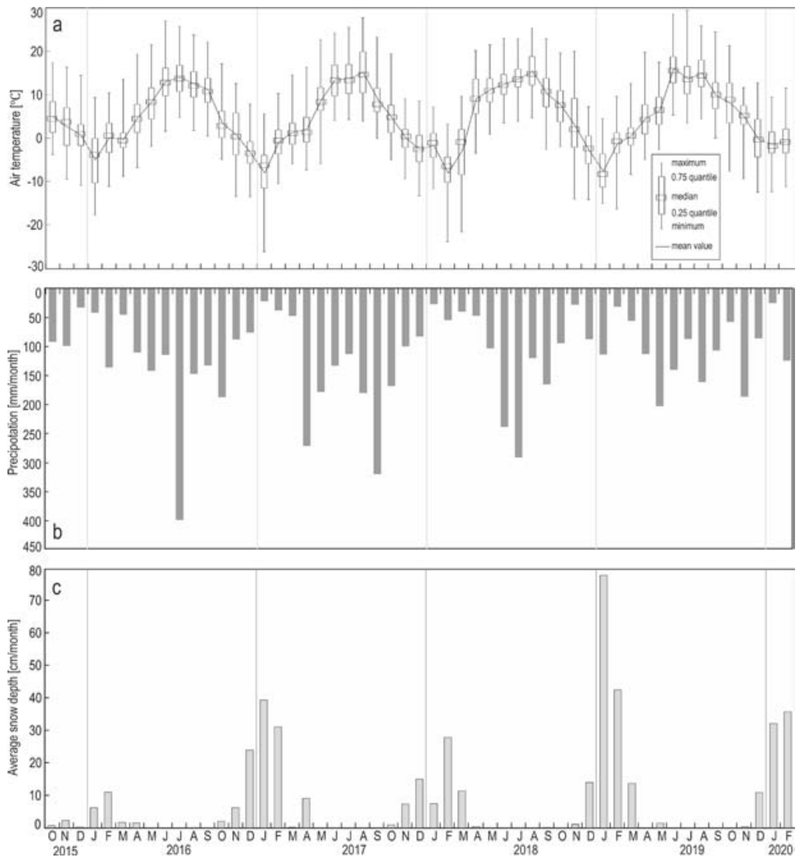

Fig. 2. Meteorological characteristics of study period: monthly air temperature (a), precipitation (b) and snow depth (c).

ning of the 20th century (Szwagrzyk et al. 2019). The share of spruce in the studied stands exceeded 90% while the share of fir and beech did not exceed 10% (Bodziarczyk et al. 2019). Until December 2013 about 93% of the Kończysta Turnia catchment was covered with forest, while almost 100% of the Pośrednia Kopka catchment was forestland (Fig. 1). The age of the forest ranged from 85 to 150 years. In December 2013 the Pośrednia Kopka catchment experienced hurricane-force winds felling 97% of its tree stands (Fig. 1). The maximum hourly average wind velocity during the windthrow event was 29 m/s (Strzyżowski et al. 2016). In the same time period, only 13% of the forest in the Kończysta Turnia catchment became disturbed (Żelazny et al. 2018). Some of the fallen trees lying across the hillslopes in the lower and central parts of the Pośrednia Kopka catchment area were removed in 2014–2015. Fir and beech seedlings were planted in a part of this area in 2015. Research work performed in 2018 showed that 23% of the disturbed area of the Pośrednia Kopka catchment was experiencing a succession of bush vegetation and juvenile trees (Żelazny et al. 2018). *Vaccinium myrtillus* L., *Rubus idaeus* L., *Athyrium distentifolium*, *Sorbus aucuparia* L., *Calamagrostis villosa*, *Deschampsia flexuosa* L., *Homogyne alpina* L., and *Oxalis acetosella* L. are the most common species, which have emerged in the disturbed area (Szwagrzyk et al. 2019). The same study also showed that in 2018 almost 50% of the forested area in the Kończysta Turnia catchment experienced an attack of the bark beetle. In 2019 a large percentage of trees on the south-facing slope of the woodland catchment became felled by high winds present in the area.

2.2. Methods of measurements

Soil temperature probes (Decagon ECH2O 5TM) were installed at two sites in each of the studied catchments. The WN and WS sites located in the studied woodland catchment represent north-facing and south-facing woodland hillslopes, respectively. The studied DN and DS sites located in the disturbed catchment represent north-facing and south-facing disturbed hillslopes, respectively. Soil temperature probes were installed in the mineral soil horizons at a depth of 20 cm. The 20 cm depth was chosen to ensure that the probes will be installed in the mineral and not the organic horizons of the soil. The probes were placed at an elevation of roughly 900 m (Fig. 1). The technical specifications of the Decagon ECH2O 5TM probes: range from −40 to 60 °C, resolution at 0.1 °C, ±1 °C. Soil temperature measurements were collected every 10 minutes. The first probes were installed in October 2015 on a north-facing slope in the woodland catchment (WN site) and on a south-facing slope in the disturbed catchment (DS site). In April 2017 probes were installed on a north-facing slope in the disturbed catchment (DN site), while in June 2017 probes were installed on a south-facing slope in the woodland catchment (WS site). The probes experienced failures several times during the study period, which explains gaps in the data set used in the study.

Meteorologic data were obtained from weather stations run by the Institute of Meteorology and Water Management in Poland. The weather stations were located in the vicinity of the study areas examined. Air temperature data measured at a height of two meters above ground level were obtained from the Polana Chochołowska station, which is located about 6 km away from the studied catchments, and found at 1,147 meters of elevation. Atmospheric precipitation data and snow cover data were obtained from the Kiry-Kościelisko station located about 1 km away from the studied catchments at an elevation of 933 meters.

Monthly soil temperature analyses were performed only for months with a complete set of data for particular study site. The coefficient of correlation for mean daily soil temperature data for the 4 study sites with respect to mean air temperature data was calculated only for months with a complete data set from all the study sites. The Pearson correlation coefficient (r) was computed. Mean daily air and soil temperatures were calculated using row data. Statistical analyses were performed in Statistica 1.3 software.

3. Results

The largest differences between the highest and the lowest values of the soil temperature over the course of the year were noted on the south-facing slope in the disturbed catchment (DS site), while the smallest were noted on the north-facing slope in the woodland catchment (WN site) (Fig. 3). In summer months (June to August) the soil temperature at the DS site usually exceeded 15 °C – it ranges from about 12.5 °C up to 20 °C in summer 2017. Soil temperatures were lower during the same period of time on the south-facing slope in the woodland catchment (WS site), where usually did not exceed 15 °C. Soil temperatures in the summer on north-facing slopes in the woodland and disturbed catchments usually ranged from 10 to 15 °C – exceeding the latter only in selected cases. Soil temperatures decreased below 5 °C in all the studied catchments in wintertime, but did not normally fall below 0 °C. Only the soil temperature at the DS site decreased below 0 °C in the winter of 2015. Soil temperatures in the spring and autumn months usually ranged from 5 to 10 °C (Fig. 3).

The smallest monthly differences in soil temperature occurred in all the studied sites in the wintertime, as evidenced by the monthly interquartile range and monthly maximum-minimum range (Fig. 3). Larger monthly differences in the soil temperature in spring, summer, and autumn in both catchments occurred on south-facing slopes (vs. north-facing), with the largest monthly dif-

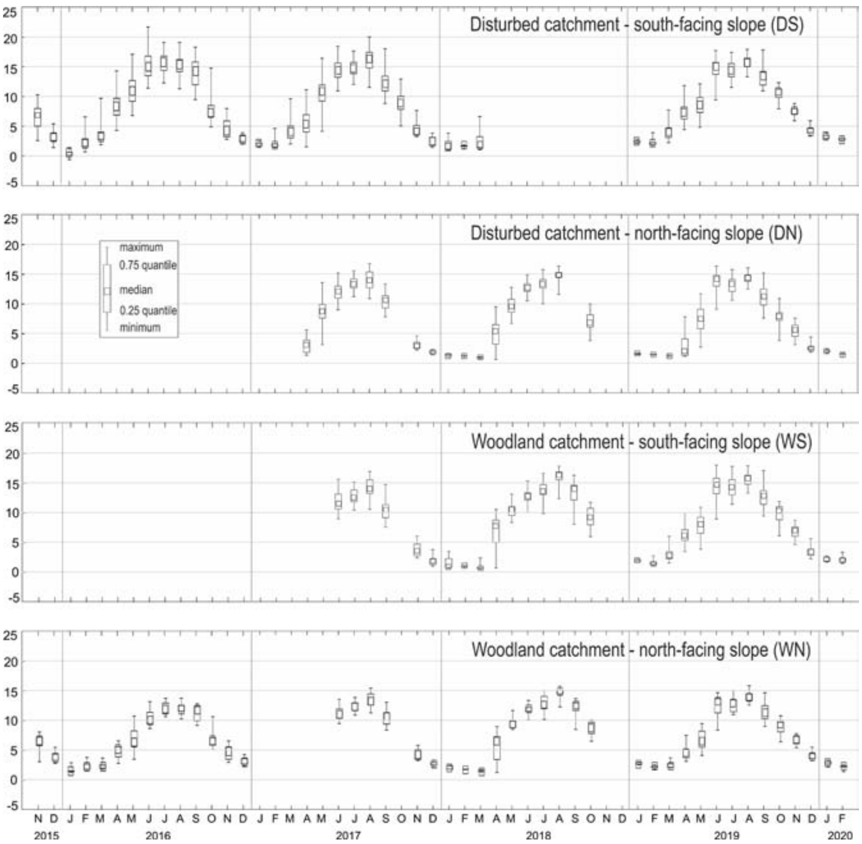

Fig. 3. Statistical characteristics of soil temperature at four studied sites for each month of the studied period (November 2015 – February 2020). The above statistics are based on raw data.

ferences in soil temperature noted at the DS site. The relationship between mean daily soil and air temperatures for a given month was stronger for south-facing slopes (DS and WS sites) than north-facing slopes (DN and WN sites). The strongest relationship was noted for the DS site and weakest for the WN site (Table 2). This relationship was strongest for all sites in the summer months and weakest in winter.

A comparison of soil temperature measured at the same time on south-facing slopes in the disturbed and woodland catchments (DS site vs. WS site) showed that in 2017 and early 2018 (January to March, lack of data for DS for subsequent months) the soil temperature at the DS site was much higher than at the WS site. Mean monthly soil temperatures in summer (June to August 2017) were from 1.8 to 2.4 °C higher at the DS site than the WS site (Table 3). These differences were smaller in the winter. This pattern changed in 2019 when soil temperatures were often higher at the WS site than the DS site, especially in the summer (Fig. 4), and mean monthly soil temperatures at both study sites were comparable (Table 3). A comparison of soil temperatures measured at the same time in both catchments on north-facing slopes (DN site versus WN site) showed that soil temperatures in the summer were higher at the DN site versus the WN site, while in the winter the situation was just the opposite – higher soil temperature values were noted for the WN site versus the DN site. This pattern was evidenced by mean monthly soil temperature data (Table 3).

Table 2. The Pearson correlation coefficient ($p \leq 0.05$) between mean daily soil temperature and mean daily air temperature for four studied sites: DS – south-facing slope of the disturbed catchment, DN – north-facing slope of the disturbed catchment, WS – south-facing slope of the woodland catchment, WN – north-facing slope of the woodland catchment (ns – not significant).

Year / month	DS	DN	WS	WN
2017 / June	0.804	0.614	0.833	0.645
2017 / July	0.845	0.644	0.758	0.443
2017 / August	0.874	0.618	0.748	0.487
2017 / September	0.774	0.628	0.707	0.572
2017 / November	0.565	0.516	0.657	0.502
2017 / December	ns	-0.392	ns	−0.395
2018 / January	0.479	0.375	0.444	ns
2018 / February	0.765	ns	0.475	0.773
2018 / March	0.571	ns	ns	−0.389
2019 / February	ns	ns	ns	ns
2019 / March	0.556	ns	0.490	ns
2019 / April	0.788	0.492	0.737	0.441
2019 / May	0.830	0.795	0.802	0.599
2019 / June	0.665	0.525	0.599	0.386
2019 / July	0.798	0.730	0.722	0.602
2019 / August	0.736	0.465	0.694	ns
2019 / September	0.613	0.606	0.652	0.538
2019 / October	0.508	0.421	0.700	0.441
2019 / November	ns	0.453	0.508	ns
2020 / January	ns	ns	ns	−0.364
2020 / February	−0.405	ns	ns	ns

In the springtime, soil temperatures first begin to increase at the DS site, with temperatures higher than

5 °C already in March. At other sites, soil temperatures begin to rise later, in April. The situation changed at the WS site in 2019 when the soil temperature at this site began to rise as quickly as that at the DS site (Fig. 3). A decrease in temperature in late autumn and winter below 5 °C is first observed on north-facing slopes in the studied disturbed catchment.

Table 3. Mean monthly soil temperature [°C] at four studied sites: DS – south-facing slope of the disturbed catchment, DN – north-facing slope of the disturbed catchment, WS – south-facing slope of the woodland catchment, WN – north-facing slope of the woodland catchment.

Year / month	DS	DN	WS	WN
2017 / June	14.3	12.0	11.9	10.9
2017 / July	14.8	13.3	12.8	12.2
2017 / August	16.1	13.9	14.3	13.3
2017 / September	12.2	10.3	10.5	10.3
2017 / November	4.5	3.0	3.8	4.1
2017 / December	2.4	1.7	1.9	2.5
2018 / January	1.8	1.2	1.5	1.9
2018 / Fabruary	1.6	1.1	1.0	1.6
2018 / March	2.4	0.8	0.9	1.3
2019 / January	2.3	1.5	1.9	2.5
2019 / Fabruary	2.1	1.3	1.4	2.0
2019 / March	4.0	1.1	2.9	2.2
2019 / April	7.3	2.9	6.2	4.5
2019 / May	8.5	7.2	7.8	6.6
2019 / June	14.6	13.7	14.5	12.4
2019 / July	14.4	13.1	14.4	12.5
2019 / August	15.7	14.2	15.6	13.7
2019 / September	13.2	11.0	12.6	11.2
2019 / October	10.6	7.6	9.9	8.8
2019 / November	7.5	5.3	6.8	6.5
2019 / December	4.3	2.5	3.4	3.9
2020 / January	3.3	1.9	2.1	2.7
2020 / Fabruary	2.9	1.4	2.1	2.1

4. Discussion

The effect of forest disturbance on the soil temperature at 20 cm depth in the study area is observable first and foremost via a rise in the soil temperature in the summer months. The mean soil temperature in the summer months on south-facing slopes in the disturbed catchment is 1.8 to 2.4 °C higher than that in the woodland catchment. After partial disturbance on the south-facing slope of the woodland catchment in 2019, the mean monthly soil temperature increased and was comparable to that in the disturbed catchment in 2013 (Table 3). The soil temperature difference on the north-facing slopes of the woodland and disturbed catchments in summertime was smaller at about 1 °C (Table 3). Higher soil temperatures in disturbed areas versus woodland areas in the summertime have been documented by many researchers in other parts of the world. The differences in mean soil temperatures described by these other researchers for the summer months between woodland and disturbed areas do vary mostly due to differences in the depth at which each measurement was performed. According to Paul et al. (2004) soil depth is the most important factor aside from other key factors such as air temperature and the surface area covered by tree canopies controlling soil temperature. Moroni et al. (2009) studied soil temperature at a depth of 10 cm in Newfoundland in Canada and found that the difference in the soil temperature between a harvested area and woodland area in the summer season equals about 2 °C. Bhatti et al. (2000) showed in northeastern Ontario in Canada that soil temperature at a depth of 5 cm increases in the summer after harvesting by 4 to 6 °C. According to research by Hu et al. (2013) conducted in a steppe area in Central Asia, the soil temperature at a depth of 10 cm was higher by 4 to 8 °C relative to that in a woodland area in the warm season. Londo et al. (1999) studied soil temperature in Texas in the United States and found a marked increase in soil temperature after deforestation – the measurements were performed at a depth of 10 cm in the summer season. The increase in soil temperature was larger after clearcutting than after partial clearcutting (Londo et al. 1999).

According to Hashimoto & Suzuki (2004) a marked increase in soil temperature following forest clear-cutting is associated with an increase in absorbed solar radiation. Soils in woodland areas are protected from heating not only by trees but also by the organic forest floor situated

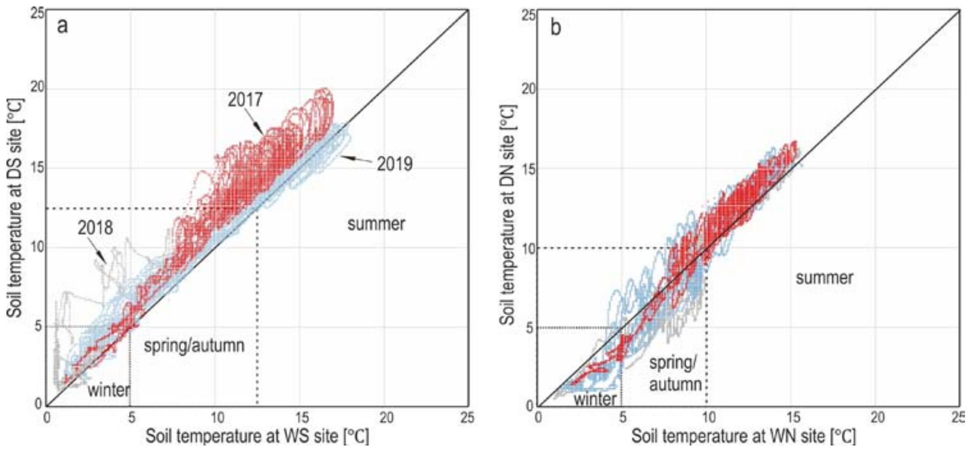

Fig. 4. Relationship between soil temperature (raw data) at DS site and WS site (A), and DN site and WN site (B) taking into account all measurements made in 2017 (red points), 2018 (grey points), and 2019 (blue points).

atop the mineral soil horizons. The forest floor acts as a thermal insulator (Bhatti et al. 2000). The presented research has shown that an area without trees and an organic layer, such as a disturbed catchment, heats up more during the summer than a wooded area with an organic layer that is 1–5 centimeters thick, as would be the case in a woodland area. The buffer effect of forest on soil temperature is confirmed by lower coefficients of correlation between soil temperature and air temperature in a woodland catchment versus a disturbed catchment.

The effect of forest disturbance on soil temperature measured at a depth of 20 cm in the winter months in the catchments examined in the present study was weaker than that in the summer. Similar conclusions were reached by Donnelley et al. (1991) for the northeastern United States, Hashimoto & Suzuki (2004) for Japan, and Moroni et al. (2009) for Newfoundland (Canada). Small differences in soil temperature in the winter between the woodland and disturbed areas examined in the present study were undoubtedly associated with the presence of snow cover and its capacity for thermal insulation. The thickness of the snow cover in the study period in the winter months usually reached into the tens of centimeters (Fig. 2c). The soil temperature is above freezing in winter months when mean daily air temperatures fall below −5 °C and sometimes below −20 °C. Short-term decline in soil temperature below 0 °C on a south-facing slope in the disturbed catchment could be due to the negligible thickness of snow cover, less than 10 cm. It is possible that the snow simply melted on the south-facing slope in the disturbed catchment. Meng et al. (1995) observed that soil frost penetrates deeply into deforested wind-exposed soil, e.g. soil without snow cover. The relatively good insulation provided by snow cover to the soil separating it from the weather above yields only a poor correlation between soil temperature and air temperature in the winter – unlike that in the summer months. According to Mellander et al. (2005), snow depth together with snow thermal conductivity play an important role in the timing of soil warming in winter and spring.

Forest disturbance leads to an increase in the difference in soil temperature over the course of the year. On south-facing slopes, this is caused by a very large increase in soil temperature in the summer; in the winter months, soil temperatures are generally somewhat higher than those in the woodland catchment. However, on north-facing slopes, this is caused by a small rise in the soil temperature in summer and a small decline in winter. The presented research has confirmed the assertion by Hu et al. (2013) that the forest buffers the soil temperature by lowering the soil temperature during the warm season and increasing it during the cold season; however, this is only true of north-facing mountain slopes. What is puzzling is the phenomenon of higher soil temperatures on south-facing slopes in winter in the disturbed catchment versus the woodland catchment. This is most likely due to increased solar radiation in disturbed areas versus woodland areas, as shown by larger diurnal changes in the soil temperature on a south-facing slope in a disturbed catchment versus all other measurement sites (unpublished data).

Soil temperatures rise in spring (>5°C), as early as March, in the disturbed catchment on south-facing slopes. At all other measurement sites, soil temperatures begin to increase only in April. Hu et al. (2013) studied soil temperature in Central Asia and observed that the spring thawing of soils occurs two weeks earlier in treeless areas (i.e. steppe) versus woodland areas. On the other hand, Whitson et al. (2005) studied soil temperatures in southwestern Canada and learned that land cover (harvested sites vs. forested sites) does not determine the timing of the spring soil thaw. Instead, slope exposure is the determining factor: the soil profiles of southerly aspect began thawing in mid-April, while those with northerly aspect in the latter half of May (Whitson et al. 2005). The presented research has shown that both land cover and slope exposure determine the timing of increases in soil temperature in spring. On south-facing slopes in disturbed areas, the snow cover disappears more rapidly than that on north-facing slopes as well as on woodland slopes. Soil on a disturbed, south-facing slope becomes devoid of snow earlier, on the one hand, and is not yet covered by young grass and bushes on the other. The lack of thermal insulation leads to increase the absorbed solar radiation triggering a rise in soil temperature. Mellander et al. (2005) assert that in years with thin snow cover there was the largest variation in the timing of soil warming (when soil temperature reaches 5 °C) in spring between stands of different age. In autumn, soil temperatures examined in the present study fall the earliest on north-facing slopes in the disturbed catchment due to both less absorbed solar radiation than on south-facing slopes and the absence of the buffer effect of forest.

The presented research represents a small step towards a better understanding that forest disturbance may lead to dangerous feedback loops in the atmosphere, pedosphere, and biosphere. The increase in soil temperature caused by forest disturbance will result in an increased release of greenhouse gases from the soil into the atmosphere. Soil temperature is a very important factor shaping methane emissions (Mikkela et al. 1995) and soil respiration – soil CO_2 efflux (Davidson et al. 1998; Subke et al. 2003; Uvarov et al. 2006; Tang et al. 2008). For example, Hick Pries et al. (2017) noted an increase in CO_2 loss of 34% to 37% from the first meter of the top mineral soil horizon with a rise of 4°C in soil temperature. The increase in greenhouse gas emissions will induce an increase in air temperature, which will result in a further increase in soil temperature and further tree mortality. Ney at al. (2019) note that forest management practices enacted following a natural forest disturbance are becoming an increasingly important part of climate change mitigation strategies.

5. Conclusions

The effect of forest disturbance triggered by hurricane-force winds on soil temperatures at a 20 cm depth in the Western Tatras in Poland is marked by an increase in the difference in the soil temperature over the course of the year. This is due first and foremost to a marked increase in soil temperature during the summer months. The mean soil temperature in the summer months on south-facing slopes in the studied disturbed catchment was 1.8 to 2.4 °C higher than that in the studied woodland catchment. On north-facing slopes, the difference in the soil temperature between the woodland catchment and disturbed catchment in the summer months was smaller at about 1 °C. The presented research has confirmed the presence of the buffer effect of forest on soil temperature in summer, which is manifested by lower coefficients of correlation between soil temperature and air temperature in the woodland versus disturbed catchment.

The effect of forest disturbance on soil temperature in the winter months is less pronounced than in the summer months. This is associated with the presence of snow cover that acts as a thermal insulator. In the winter months (December-February) snow cover depth usually exceeds 20 cm in the studied area. Good insulation of the soil from the atmosphere by snow cover leads to a very weak relationship between soil temperature and air temperature in winter. The soil temperature on disturbed, north-facing slopes in the winter is lower than that on woodland, north-facing slopes. This suggests the presence of a buffer effect of forest on the soil temperature that increases the soil temperature during the colder season and decreases it in the warmer season, on north-facing slopes. However, it is puzzling that a south-facing slope in a disturbed catchment would exhibit slightly higher soil temperatures in winter than those in a woodland catchment. This is likely due to increased absorbed solar radiation on south-facing slopes in disturbed areas versus woodland areas. However, this finding requires further research.

The research has shown that land cover (i.e. forest vs. lack of forest) and slope exposure (south versus north) determine the timing of increases in soil temperature in spring and timing of soil temperature declines in autumn. In the spring season, soil temperatures increase the fastest (in March) on disturbed, south-facing slopes due to faster thawing of snow and absence of any vegetation such as young grasses or bushes. Given a low level of thermal insulation, one may expect increased absorbed solar radiation that leads to a rapid increase in soil temperature. In the autumn season, temperatures on the studied disturbed, north-facing slopes decrease at an earlier date than elsewhere due to less absorbed solar radiation than on south-facing slopes as well as the lack of the buffer effect of forest cover.

The present study shows that an increase in soil temperature triggered by forest disturbance may significantly intensify soil warming caused by climate warming. Moreover, forest disturbance will lead to dangerous feedback mechanisms. The increase in soil temperature caused by forest disturbance will cause increased emissions of CO_2 from the soil to the atmosphere, which will contribute to an increase in air temperature. This will result in a further increase in soil temperature and the decline of some temperature sensitive tree stands. In order to minimize the soil warming effect triggered by forest disturbance, tree seedlings should be planted as soon as possible after forest disturbance. Moreover, this type of situation should be used to plant stands whose tree species composition corresponds to the natural habitat in a given climate zone in the mountains. Natural forest stands are believed to be more resistant to natural disasters such as hurricane-force winds or bark beetle invasions than spruce monocultures frequently found in Central Europe.

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References

Allen, C. D., 2009: Climate-induced forest dieback: an escalating global phenomenon? Unasylva, 231/232:43–49.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M. et al., 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management, 259:660–684.

Allen, M. R., Dube, O. P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys, S. et al., 2018: Framing and Context. In: Masson-Delmotte, V., Zhai, P., Pörtner, H-O., Roberts, D., Skea, J., Shukla, P.R. et al. (eds): Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change.

Anderegg, W. R. L., Kane, J. M., Anderegg, L. D. L., 2013: Consequences of widespread tree mortality triggered by drought and temperature stress. Nature Climate Change, 3:30–36.

Bhatti, J., Fleming, R. L., Foster, N. W., Meng, F-R., Bourque, C. P. A., Arp, P., 2000: Simulations of pre- and post-harvest soil temperature, soil moisture, and snowpack for jack pine: comparison with field observations. Forest Ecology and Management, 138:413–426.

Bodziarczyk, J., Szwagrzyk, J., Zwijacz-Kozica, T., Zięba, A., Szewczyk, J., Gazda A., 2019: The structure of forest stands in the Tatra National Park: The results of 2016–2017 inventory. Forest Research Papers, 80:13–21.

Cassardo, C., Park, S. K., Sungmin, O., Galli, M., 2018: Projected Changes in Soil Temperature and Surface Energy Budget Components over the Alps and Northern Italy, Water, 10:1–18.

Davidson, E. A., Janssens, I. A., 2006: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440:165–173.

Donnelly, J. R., Shane, J. B., Yawney, H. W., 1991: Harvesting causes only minor changes in physical properties of upland Vermont soil. Northern Journal of Applied Forestry, 8:33–36.

Gholami, V., 2013: The influence of deforestation on runoff generation and soil erosion (Case study: Kasilian Watershed). Journal of Forest Science, 59:272–278.

Hashimoto, S., Suzuki, M., 2004: The impact of forest clear-cutting on soil temperature: a comparison between before and after cutting, and between clearcut and control sites. Journal of Forestry Research, 9:125–132.

Hess, M., 1996: Klimat. In: Mirek, Z., Głowaciński, Z., Klimek, K., Piękoś-Mirkowa, H. (eds.): Przyroda Tatrzańskiego Parku Narodowego, Tatry i Podtatrze 3. Tatrzański Park Narodowy. Kraków–Zakopane, p. 53–68.

Hlásny, T., Kočický, D., Maretta, M., Sitková, Z., Barka, I., Konôpka, M., Hlavatá, H., 2015: Effect of deforestation on watershed water balance: hydrological modelling-based approach. Central European Forestry Journal, 61: 89–100.

Hu, G., Liu, H., Anenkhonov, O. A., Korolyuk, A. Y., Sandanov, D. V., Guo, D., 2013: Forest buffers soil temperature and postpones soil thaw as indicated by a three-year large-scale soil temperature monitoring in the forest-steppe ecotone in Inner Asia. Global and Planetary Change, 104:1–6.

Hu, Q., Feng, S., 2003: A daily soil temperature dataset and soil temperature climatology of the contiguous United States. Journal of Applied Meteorology, 42:1139–1156.

Iwahana, G., Machimura, T., Kobayashi, Y., Fedorov, A., Konstantinov, P., Fukuda, M., 2005: Influence of forest clear-cutting on the thermal and hydrological regime of the active layer near Yakutsk, Eastern Siberia. Journal of Geophysical Research, 110:G02004.

Jewett, K., Daugharty, D., Krause, H., Arp, P., 1995: Watershed responses to clear-cutting: effects on soil solutions and stream water discharge in central New Brunswick. Canadian Journal of Soil Science, 75:475–490.

Khaleghi, M. R., 2017: The influence of deforestation and anthropogenic activities on runoff generation. Journal of Forest Science, 63:245–253.

Likens, G. E., Bormann, F. H., Johnson, N. M., Fisher, D. W., Pierce, R. S., 1970: Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook Watershed-Ecosystem. Ecological Monographs, 40:23–47.

Londo, A. J., Messina, M. G., Schoenholtz, S. H., 1999: Forest harvesting effects on soil temperature, moisture, and respiration in a bottomland hardwood forest. Soil Science Society of America Journal, 63:637–644.

Martínez-Vilalta, J., Lloret, F., Breshear, D. D., 2012: Drought-induced forest decline: causes, scope and implications. Biology Letters, 8:689–691.

Mellander, P. E., Laudon, H., Bishop, K., 2005: Modelling variability of snow depths and soil temperatures in Scots pine stands. Agricultural and Forest Meteorology, 133:109–118.

Meng, F-R., Bourque, C-A., Jewett, K., Daugharty, D., Arp, P. A., 1995: The Nashwaak Experimental Watershed Project: analysing effects of clearcutting on soil temperature, soil moisture, snowpack, snowmelt and stream flow. Water, Air and Soil Pollution, 82:363–374.

Moroni, M., Carter, P., Ryan, D., 2009: Harvesting and slash piling affect soil respiration, soil temperature, and soil moisture regimes in Newfoundland boreal forests. Canadian Journal of Soil Science, 89:343–355.

Ney, P., Graf, A., Bogena, H., Diekkrüger, B., Drüe, C., Esser, O. et al., 2019: CO_2 fluxes before and after partial deforestation of a Central European spruce forest. Agricultural and Forest Meteorology, 274:61–74.

Paul, K. I., Polglase, P. J., Smethurst, P. J., O'Connell, A. M., Carlyle, C. J., Khanna, P. K., 2004: Soil temperature under forests: a simple model for predicting soil temperature under a range of forest types. Agricultural and Forest Meteorology, 121:67–182.

Schlesinger, W. H., Andrews, J. A., 2000: Soil respiration and the global carbon cycle. Biogeochemistry, 48:7–20.

Skiba, S., Koreň, M., Drewnik, M., Kukla, J., 2015: Soils. In: Dąbrowska, K., Guzik, M. (eds.): Atlas of the Tatra Mts. – Abiotic Nature. Tatrzański Park Narodowy. Zakopane, plate number: VI.1.

Steinkamp, J., Hickler, T., 2015: Is drought-induced forest dieback globally increasing? Journal of Ecology, 103:31–43.

Strzyżowski, D., Fidelus-Orzechowska, J., Żelazny, M., 2016: Geomorphological changes within a hillslope caused by a windthrow event in the Tatra Mountains, Southern Poland. Geografiska Annaler. Series A, Physical Geography, 98:347–360.

Szwagrzyk, J., Bodziarczyk, J., Pielech, R., Zieba, A., Zwijacz-Kozica, T., 2019: The impact of wind and bark beetle outbreaks and protective measures on the vegetation of spruce forests in the Tatra National Park. Parki Narodowe i Rezerwaty Przyrody, 38: 57–68.

Ustrnul, Z., Walawender, E., Czekierda, D., Šťastný, P., Lapin, M., Mikulová, K. 2015: Precipitation and snow cover. In: Dąbrowska, K., Guzik, M. (eds.): Atlas of the Tatra Mts. – Abiotic Nature. Tatrzański Park Narodowy. Zakopane, plate number: II.3.

Whitson, I., Chanasyk, D., Prepas, E., 2005: Effect of forest harvest on soil temperature and water storage and movement patterns on boreal plain hillslopes. Journal of Environmental Engineering and Science, 4:429–439.

Żelazny, M., Adamska, M., Ciemborowicz, M., Fidelus-Orzechowska, J., Gus, M., Jaśkowiec, B. et al., 2018: Ocena wpływu wielkoobszarowych wiatrołomów na reżim hydrochemiczny i denudację zlewni położonych w obszarach leśnych na terenach górskich (Tatry Polskie) – etap 4. Kraków, Raport K/KDU/000494, 395 p.

Żmudzka, E., Nejedlík, P., Mikulová, K., 2015: Temperature, thermal indices. In: Dąbrowska, K., Guzik, M. (eds.): Atlas of the Tatra Mts. – Abiotic Nature. Tatrzański Park Narodowy. Zakopane, plate number: II.2.

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Influence of different exposition of larch wood facade models on their surface degradation processes

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Abstract

Wood, as a building material, is nowadays more often used outdoors. From the point of view of environment care, wood constructions and use of renewable materials belongs between modern increasing trends in industry. Wooden facades, more often used without surface treatment, are the important part of this trend. In Central Europe, European larch *(Larix decidua)* and Siberian larch *(Larix sibirica)* are especially popular materials for wooden facade elements. The aim of this study is to characterize the surface degradation of untreated facade models from both European and Siberian larch wood. The wood species, orientation to the sides of the world and construction type of the facade were the evaluation factors, which were regularly examined during 24 months of outdoor exposure via measuring the changes of surface colour, gloss, wettability and visual appearance in the form of cracks and resin leaking. The influence of all evaluated factors on the measured properties was determined. The results of this work can help to proper use of untreated larch wood on facade elements in practice.

Key words: colour changes; facades; larch wood; surface degradation; weathering

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1. Introduction

Wood, as a building material, is well known for many advantages. But there is a need to use it in a way to protect it against some specific factors, which negatively affect its service life, functionality and appearance. This process is called bio-degradation (Hrapková 2012). According to study of Gielen (1997), the production of all building materials is responsible for 8 – 12% of all CO_2 emissions in Western Europe. The use of wood as a building material can reduce this number (Goverse et al. 2001; Bribiàn et al. 2011). Already in the last century the trend of ecological construction became familiar and the modern wood constructions are the proof that wood still belongs between popular and abundantly used building materials (Ingo 2011; Kržišnik 2018).

Untreated wood, as a material for facade, can be a cost-effective alternative to materials with an applied coating system, as it requires limited maintenance. On the other hand, more information about final costs, environmental impact of building components and service life are needed (Feist & Hon 1984). In the study of Gupta et al. (2011), the FTIP analysis was used to estimate the prediction of service life of wooden facade elements. Based on their results, the key is to understand the degradation processes of untreated wood during weathering. Generally, the prediction of service life of wood components is the main factor of research, which requires careful examination of material´s properties (Brischke et al. 2008; Gupta et al. 2011). Current trends even favor facade elements without surface treatment, even though the visual appearance of untreated wood changes over time due to weather conditions (Feist & Hon 1984; Hirche 2014; Lesar et al. 2016).

Wooden facades are usually made from softwoods and used more and more often without surface treatment (Ingo 2011). According to Connell (2004), during last decade there was a trend of increasing application of domestic wood species. The reasons for that are the lower costs of transport, lower emission of CO_2 and negative perception of tropical wood use, which is often connected with deforestation (Sohngen et al. 1999). In the area of Czech Republic, there are several domestic wood species, which are suitable for facade production – spruce, fir, larch and Douglas fir among softwoods and oak, Black locust or chestnut among hardwoods. But practically, hardwoods are not used at all for this purpose. The reason are more disadvantages of more durable hardwoods (for example *Quercus* sp. or *Robinia pseudoacacia*) – their

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higher density (Požgaj et al. 1993) and thus increased facade weight, higher price and also higher susceptibility of lumber to shape deformations and formation of larger cracks. Furthermore, various types of thermally modified wood are used, preferably made of Scots pine or Norway spruce (Reinprecht 2016). The most important factors for the selection of suitable wood species are the number and width of annual rings – the denser annual rings stands for higher durability of wood (Ingo 2011). Frequently used larch wood belongs to the durability class 3 according to EN 350 (2016). European larch (*Larix decidua* Mill.) is characterized with distinguished sapwood and heartwood, sapwood is narrow and yellowish, heartwood is from red-brown to red-purple colour and turns dark on the air (Wagenführ 2003; Gierlinger et al. 2003). European larch wood does not have a lot of resin canals but they can be recognized in all directions well known for wood structure – radial, tangential and longitudinal. This wood species is dimensionally stable a relatively resistant to acids, climatic changes and attack of insects and fungi (Musil 2007). Sapwood of Siberian larch (*Larix sibirica*) is yellow, heartwood is red-brown. Siberian larch wood is also known for high mechanical resistance and strength in compression and relatively low water absorption. Due to the high content of terpenoids it is durability to biotic and abiotic factors (Gierlinger et al. 2003). Siberian larch is highly resistant to atmospheric factors, in practice, it is considered as durable wood, which can be used in construction without any protection. Both European and Siberian larch are characterized with high strength, which gives a high percentage of use in furniture and construction (Gierlinger et al. 2003; Musil 2007).

Wood exposed to outdoor conditions is subjected to process of natural weathering, when wood degrades due to the effect of atmospheric factors and changes its surface properties both on macroscopic and microscopic level (Williams 2007). The degree of degradation is generally influenced by wood density, amount of sapwood and heartwood, annual ring´s orientation and content of lignin and extractives (Williams 2005). Abiotic factors cause atmospheric degradation of wood, which negatively affects only its surface layers (Temiz et al. 2005; Evans 2008; Oberhofnerová et al. 2017) but it can be beginning of more dangerous degradation caused by biotic factors – wood-destroying fungi and insects (Feist and Hon 1984; Reinprecht 2012). The changes take place only to the depth of few millimetres and do not affect the important mechanical properties, service life or even the function of wooden element (Gobakken et al. 2011). The most significant factors influencing the rate of degradation are solar radiation and water, acting synergistically (Tolvaj& Faix 1995; Hon & Shiraishi 2001; Müller et al. 2003). Ultraviolet (UV) radiation provokes photochemical reactions, which cause the decomposition of lignin, extractives and partly hemicellulose (Feist & Hon 1984; Pandey 2005; Reinprecht 2008). In the first phase, the lignin is decomposed. As a result, in indoor applications the wood turns dark, but in outdoors the decomposed parts are washed out by rainwater from the surface (Tolvaj 1995; Pandey 2005). Due to that process, the light shade of wood caused by light colour of non-degraded cellulose is formed, but it is immediately disrupted by deposition of dust particles and pollution into the porous structure of wood surface (Evans 2008). The well known greying of wood surface in exterior takes place. After leaching the products of photodegradation the layers of wood cells are further exposed and eroded (Feist 1982; Williams & Feist 1999; Reinprecht 2008). The other factors affecting the intensity of surface degradation are temperature, acid rains and wind (Feist 1990; Williams 2005; Evans 2008; Teacà et al. 2013). The effect of wind is evident in formation of typical plastic structure of wood in exterior, which is manifested by increased roughness of surface. The uneven surface is caused mainly by the different density of early wood and late wood, which is more obvious at softwoods (Williams 1999).

Other important factors influencing weathering of wood are biotic factors and combination of wood product application and construction or design solution (Sandak et al. 2017). When applying untreated wood elements on facade, the principles of construction protection should be respected in order to significantly reduce the weathering process (EN 335; Ganne-Chédeville et al. 2012). The basic point of construction protection is keeping the optimal shape and connection of wooden facade element in order to ensure the rainwater drain. Other principles are suitable roof overhangs, which can significantly reduce the exposition of wood facade to water, or avoiding the contact of wood with ground (Ingo 2011). Geographic and climatic factors plays an important role as well in weathering. In the study of Mohebby & Saei (2015) the influence of different cardinal points on weathering was confirmed – facades exposed to south side are more affected by intensive solar radiation and changes of relative humidity and temperature, therefore the higher protection of facade is recommended for this side. The intensity of solar radiation is lower at north side, on the other hand it is more exposed to higher humidity and slower drying out of wood, which makes suitable conditions for growth of wood-destroying fungi and moulds causing colour changes of wood (Reinprecht 2016). In the climatic conditions of Central Europe, the western side is more influenced by the predominant direction of winds and incident rainfall compared to the eastern exposure. The western side is more influenced by the predominant direction of winds and incident rainfall compared to the eastern exposure in the climatic conditions of Central Europe.

The aim of this study is to determine the influence of wood species, different exposure to cardinal points (south and north) and different type of construction on the surface changes of untreated wood facade elements. Facade models were made from European (*Larix* *decidua*) and, still more frequently used, Siberian larch (*Larix sibirica*) and they were exposed to weathering conditions in Prague (Czech Republic) in Central Europe for 24 months. The results of this study could help to understand behaviour of larch wood in exterior and its application in the form of facade cladding and to understand aesthetical changes of untreated wood during weathering.

2. Materials and methods

2.1. Preparation of samples

Based on the analysis of currently used wooden cladding, the two types of construction profiles (type A and B) and their placement were designed in software AutoCad. The accent was put on the elimination of rainwater and its faster drain from the wood surface (Fig. 1). The facade models were made from European larch (EL) and Siberian larch (SL), which were prepared in dimensions of cladding of 400 × 145 × 20 mm (length x width x thickness). The overall size of the facade models was 400 × 600 mm (width × length). The facade models were marked by the wood species, type of construction and exposure (f. e. SL–B–S, see Table 1).

Table 1. Marking of the facade models.

Wood species	Construction type	Exposure
Siberian larch (SL) × European larch (EL)	Type A × Type B	(South) S × (North) N

Profiled cladding was sanded by sandpaper with 120 grain and then attached by fasteners to spruce wood supporting construction from the south (S) and north (N) side. These facade models were subsequently exposed in exterior stands in the inclination of 90° (Fig. 2). Before exposition, the samples were showed 18% of wood moisture content.

The natural weathering test took place in Czech Republic at Suchdol (50° 07´49,68 "N; 14° 22´13,87" E, 285 m elevation above sea level) for 24 months based on the EN 927–3 (2006). Testing stand with facade models was placed at the roof of Pavilion of Wood Sciences of Faculty of Forestry and Wood Sciences in Prague.

Fig. 2. The placement of facade models in the testing stands in exterior in 90°.

The selected surface properties were regularly examined before and after 6, 12 and 24 months of exposure: changes of gloss and colour, wettability (via measuring contact angle) and visual evaluation focused on the cracks forming and resin leaking.

2.2. Colour measurements

Colour parameters L*a*b* were determined using the spectrophotometer CM-600d (Konica Minolta, Japan) at the same marked places on the specimens. The device was set to an observation angle of 10°, d/8 geometry and D65 light source in L*a*b* colour space (according to the Commission International de l´Eclairage – CIE 1986). Forty measurements were carried out for each

Fig. 1. Design of facade profiles – type A (left – Siberian larch) and B (right – European larch). Type A is characterized with cladding top cut in 45°, while type B was designed with inclination 30° and rounded top with radius r = 15 mm.

tested model – twenty for south exposure and twenty for north exposure. For the mathematical expression of difference of two colours is used the Euclidian distance – called as total colour difference ΔE*. The total colour difference was calculated using the following equation [Equation 1]:

$$E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad [1]$$

where:
L is the lightness from 100 (white) to 0 (black), a* is the chromaticity coordinate from −60 (green) to + 60 (red), b* is the other chromaticity coordinate from −60 (blue) to +60 (yellow)* (Sehlstedt-Persson 2003).

2.3. Gloss measurements

Gloss measurements were performed based on EN ISO 2813 (2014) using glossmeter MG268-F2 (KSJ, Quanzhou, China). Forty measurements at a 60° angle per sample (twenty for south side, twenty for north side) were performed during weathering.

2.4. Contact angle measurements

The sessile drop method with static contact angle measurement (without external interference) was performed using the methodology of Bastani et al. (2015). The wettability measurements were taken using a goniometer Krüss DSA 30E device (Krüss, Hamburg, Germany) on radial surfaces of wood samples before weathering and after 24 months. From each model, the samples from the south and north side after 24 months of exposure were prepared – in dimensions 70 × 30 × 20 mm (l × w × t). Ten measurements were taken for each sample, with distilled water drops with a dosing volume of 5 µl. The contact angle values were determined after 5 s of drop deposition to reach the equilibrium point and prevent the risk of contamination with extractives. The phenomena of spreading and absorption of drops on the wood surface was investigated via comparison between initial and weathered state of wood samples.

2.5. Visual evaluation

The formation of cracks and degree of surface degradation were evaluated before and after weathering using visual evaluation on the base of EN ISO 4628 (2003).

2.6. Statistical analysis

The statistical evaluation was performed using Statistica 12 software (Statsoft, Palo Alto, USA) and MS Excel 2013 (Microsoft, Redmond, USA) using mean values, standard deviations, whiskers plots and analysis of variance (ANOVA).

3. Results and discussion

The total colour difference *ΔE**, calculated from the measured values (*L*, a*, b**), was the most significant factor indicating weathering of facade models. The specific colour parameters (*L*, a*, b**) represents the change of colour more accurately. During exposure of face models in exterior there was a significant change of colour, at the end of the experiment almost all the tested models were characterized with the total colour difference ΔE* > 12. This value is considered as different colour in comparison with the initial colour at the beginning of the experiment. An exception was recorded for facade models SL–B–S and EL–B–S, which were characterized with the total colour change ΔE* = 9.9 and 11.2 respectively. These values are considered as high colour change only (Sehlstedt-Persson 2003). The most significant colour changes were noted after 24 months of exposure for the facade models exposed to north side, specifically SL–A–N, EL–A–N. Regarding south side, the most significant colour difference was recorded for the model SL–A–S with the values *ΔE** = 19.3 (Fig. 3).

When evaluating the colour parameter L *, a negative difference of its values was initially observed, which means that the colour of the facade models gradually changed to a darker shade. This change is mostly caused by the deposition of dust particles in exterior and by the

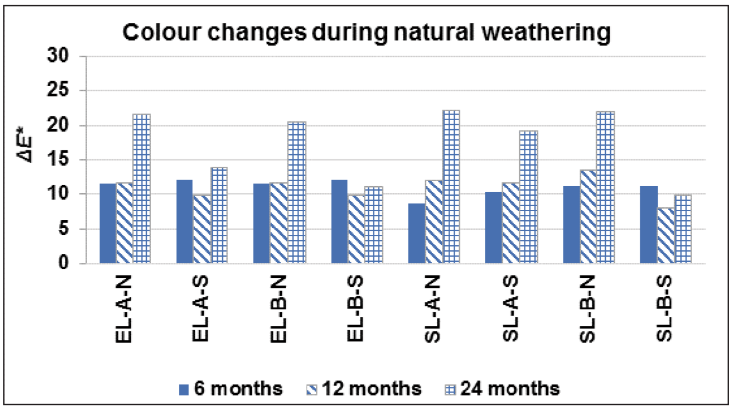

Fig. 3. Total colour changes *ΔE** of facade models during natural weathering.

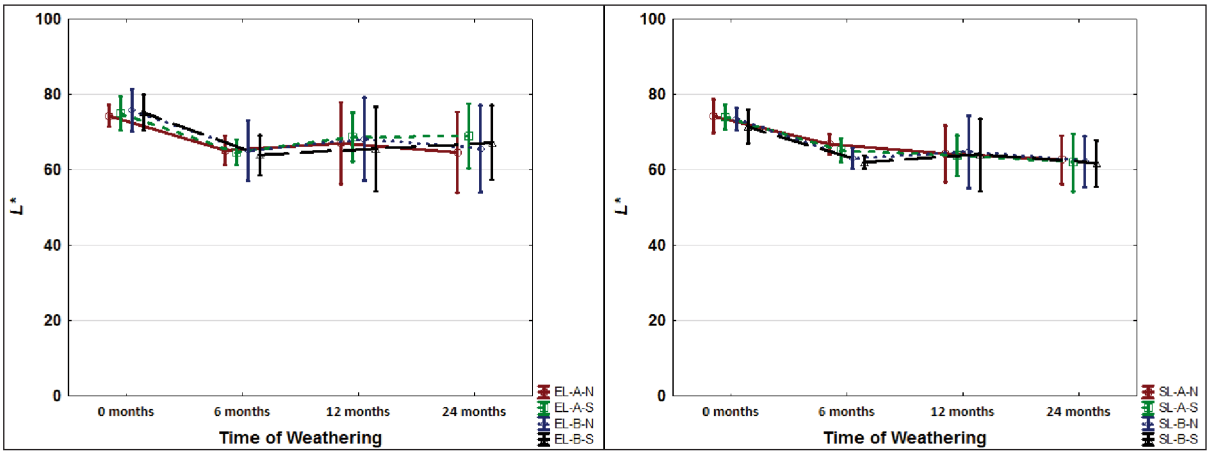

Fig. 4. 2SD whiskers plots and Mean values of *L** changes during natural weathering of facade models from European (left) and Siberian (right) larch.

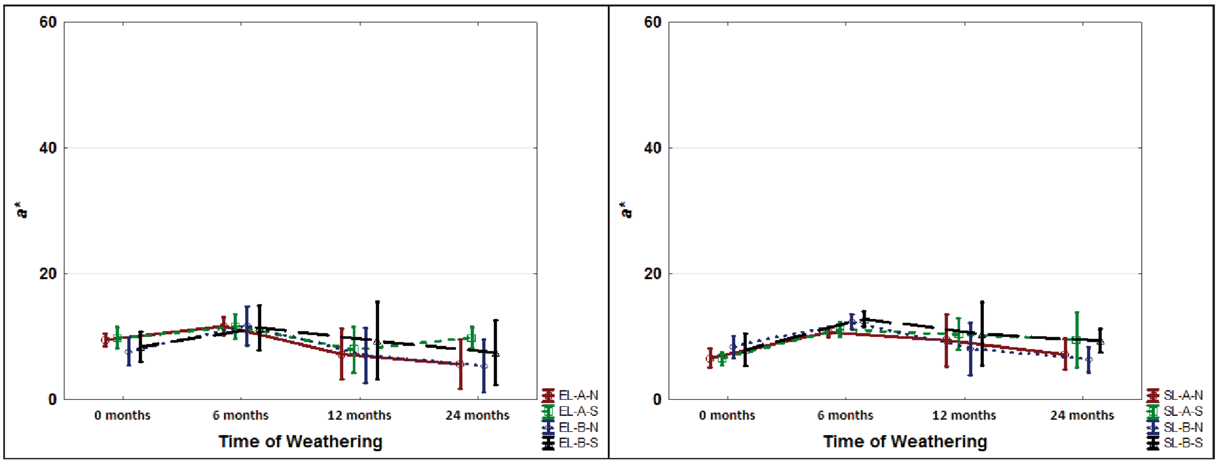

Fig. 5. 2SD whiskers plots and Mean values of *a** changes during natural weathering of facade models from European (left) and Siberian (right) larch.

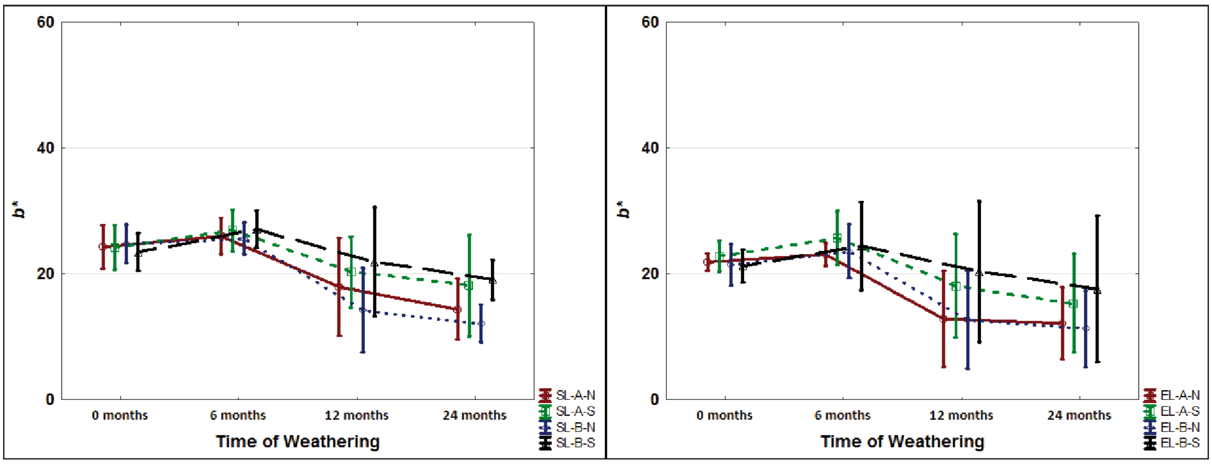

Fig. 6. 2SD whiskers plots and Mean values of *b** changes during natural weathering of facade models from European (left) and Siberian (right) larch.

photodegradation of extractives and lignin on wood surface (Oberhofnerová et al. 2017). The most significant difference in the values of the parameter ΔL* was clearly observed at the facade models of type A, specifically in the Siberian larch (SL) on the north side (N) with ΔL* = −17.9. The second highest value was recorded for the same model on the south side with ΔL * = −17.0. From the point of view of this indicator of lightness, the construction type A model exposed to north side was less suitable for both wood species. For construction type B, due to its specific inclination of the façade profiles greater than 90° (see Fig. 1), there was less deposition of impurities in the porous structure and micro-cracks of the wood. The European larch on the south side best suited the construction type A of facade model. Facade models SL–B–S and EL–A–S type showed the lowest differences in lightness values.

The colour parameters a* and b* increased after 6 months of exposure, which is caused by the photodegradation of lignin (Müller 2003), but after 12 months this trend was completely opposite and during the exposure the values kept decreasing, which is due to gradual leaching of lignin (Pastore et al. 2004). All facade models exposed to natural weathering for 6 months showed a trend of increasing values of the parameter a*. After 12 months of exposure, all models showed a decrease in these values. The most significant decrease was recorded for the EL–B–N and EL–A–N models. On the contrary, the least significant decrease in a* values was measured for the SL–B–S and SL–A–S models. Overall, the north side and the European larch generally showed lower values of a*. The highest value of the parameter b* was recorded after 6 months of exposure for model SL–B–S (b* = 27.1) and model SL–A–S (b* = 26.9). At the end of the weathering, the most significant decrease of the parameter b* was measured at model EL–A–N (b* = 7.1) and SL–B–N (b* = 7.9). According to the dimensional colour model, the facade models approached the yellow hue in the 6th month and the blue hue from the 12th month until the end of the test. The colour parameter b* showed lower values of European larch compared to European larch, and lower values were also measured for the facade models on the north side than on the south side.

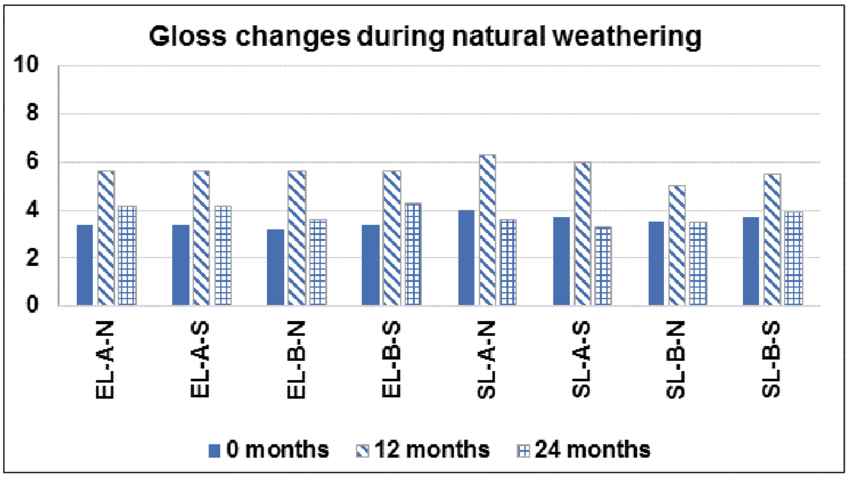

Fig. 7. Gloss changes of facade models during natural weathering.

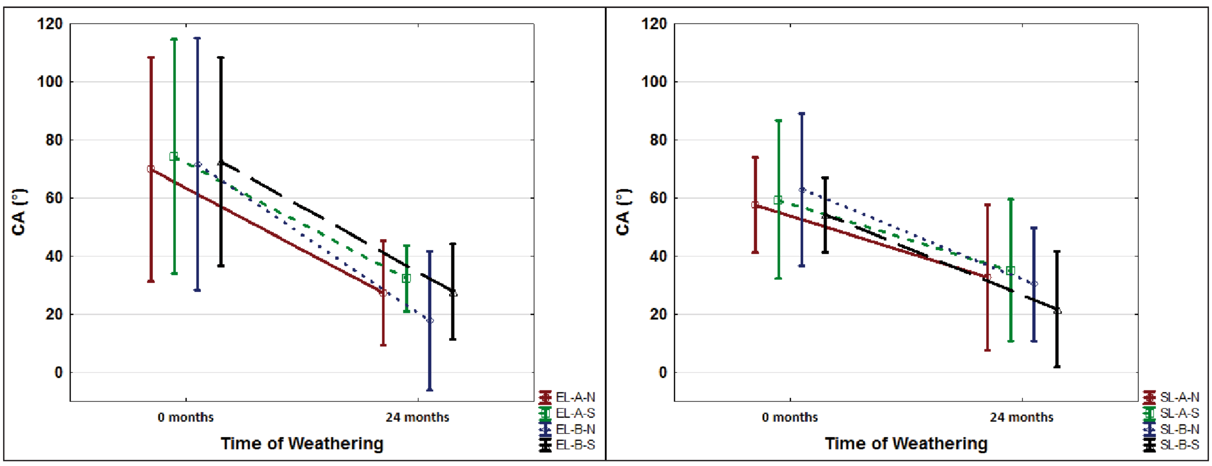

Fig. 8. Surface wetting of facade models before and after natural weathering.

The wood of both types of tested larch had a matt surface (EN ISO 2813 2014) even before the start of the weathering (Fig. 7). During the test, there was a slight increase after 12 months of weathering and a decrease again to almost original values after 24 months of exposure. Despite some slight differences in the initial values and the course of changes, the gloss values are so low that they do not play an important role in the visual perception of the facade cladding for the external observer.

The contact angle of surface wettability with water showed considerable variability due to the inhomogeneous structure of larch wood even before weathering (Fig. 8). This inhomogeneity was slightly lower at SL with higher density of annual rings, where the deposited drop with a volume of 5 µl always partially affected the zone of early wood and late wood. For EL with wider annual rings, the variability was higher. The places with a higher resin content were other reason for the variability of results (see photos in Fig. 1). After weathering, significant decrease in contact angle values (CA°) and a decrease in variability of EL were observed. This action was due to the gradual photodegradation and leaching of hydrophobic lignin from wood surfaces (Pastore et al. 2004). In general, lower CA° values were measured for facade model B (lowest for EL–B–N), but the differences were not statistically significant (Fig. 8). The decrease is not as significant as in study of Oberhofnerová & Pánek (2016), which is, however, due to the 90° inclination of the wood in this experiment, where there is no such rapid weathering compared to exposure in the inclination of 45° according to EN 927–3 (2006).

Visual evaluation of facade models confirmed more significant formation of cracks at SL–A–S in comparison with other models. These visual changes were observed after 12 months of weathering (Fig. 9). In this Figure, it is also possible to see typical greying of wood in exterior.

In some cases, resin leaking was observed, especially in the first 12 months of exposure (Fig. 10). This characteristic was the most pronounced at SL–B–S model.

The colour changes were observed even by naked eye, which confirms the values of total colour difference measured by spectrophotometer (Fig. 3).

4. Conclusion

Two construction types of facade models were made from European Larch (*Larix decidua Mill.*) and Siberian Larch (*Larix sibirica*). These models were subjected to natural weathering for 24 months on the south and north exposure. The colour changes at all models were significant, the lowest changes were observed for SL–B–S model. But in general, the most significant overall colour changes were paradoxically shown by the facade models made of Siberian larch. In terms of the indicator of total colour difference, the European larch reached in more cases better results than Siberian.

In terms of type of exposure, the north side showed higher colour changes compared to the south side.

Fig. 9. The formation of cracks – visual appearance of Siberian larch after 12 months of exposure to south side, construction type A.

Fig. 10. The resin leak after 12 months of weathering at Siberian larch exposed to south side, construction type B.

Another evaluation parameter was the gloss, where, however, due to its low initial values and small changes, the visual characteristics of the facade models were not significantly affected. A more significant decrease in the contact angle of wettability was observed for European larch and for facade model B, but the differences after weathering were not statistically significantly different due to the large variability of the measured values. There was a higher formation of cracks on Siberian larch wood in comparison with European larch. Cracks were observed on both types of exposure (N×S) and construction models (A×B) but the most at the facade model A on the south side. The occurrence of resin leaking during outdoor exposure was also observed, especially in the first 12 months of exposure.

Finally, the main result of this work is that changes of larch façade appearance during exterior exposure depend not only on kind of larch wood, north or south exposure, but important factor is also design of profiles in construction.

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References

Bastani, A., Adamopoulos, S., Militz, H., 2015: Water uptake and wetting behaviour of furfurylated, *N*–methylol melamine modified and heat-treated wood. European Journal of Wood and Wood Products, 73:627–634.

Bribiàn, I. Z., Capilla, A. V., Usón, A. A., 2011: Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and Environment, 46:1133–1140.

Brischke, C., Rapp, A. O., 2008: Dose–response relationships between wood moisture content, wood temperature and fungal decay determined for 23 European field test sites. Wood Science and Technology, 42:507–518.

Connell, M., 2004: Issues Facing Preservative Suppliers in Changing Market for Treated Wood (COST E22, Brussels), 8 p.

Evans, P. D., 2008: Weathering and photo-degradation of wood. Development of Wood Preservative Systems, ACS Symposium Series, American Chemical Society, p. 69–117.

Feist, W. C., 1982: Weathering of wood in structural uses. In: Structural use of wood in adverse environments. Van nostrand reinhold, p. 156–178.

Feist, W. C., 1990: Outdoor wood weathering and protection. In: Archaeological wood: properties, chemistry, and preservation. Advances in Chemistry Series 225. Proceedings of 196th meeting of the American Chemical Society, p. 25–28.

Feist, W. C., Hon, D. N.-S., 1984: Chemistry of weathering and protection. In: R. M. Rowell (ed.): The Chemistry of Solid Wood (Washington, DC: American Chemical Society), p. 401–451.

Ganne-Chédeville, Ch., Jääskeläinen, A. S., Froidevaux, J., Hughes, M., Navi, P., 2012: Natural and artificial ageing of spruce wood as observed by FTIR-ATR and UVRR spectroscopy. Holzforschung, Berlin, 66:163–170.

Gielen, D., 1997: Building Materials and CO2 – Western European Emissions Reduction Strategies. MATTER Project Report (Petten: Netherlands Energy Research Foundation (ECN)).

Gierlinger, N., Jacques, D., Schwanninger, M., Wimmer, R., Pâques, L. E., 2003: Heartwood extractives and lignin content of different larch species (*Larix* sp.) and relationships to brown-rot decay-resistance. Trees, 18:230–236.

Gobakken, L. R., Høibø, O. A., 2011: Aesthetic service life of coated and uncoated wooden cladding-influencing factors and modelling. In: The 42nd Annual Meeting of IRG. International Research Group on Wood Protection IRG/WP, 11-20470:20.

Goverse, T. et al., 2001: Wood innovation in the residential construction sector; opportunities and constraints. Resources, Conservation and Recycling, 34:53–74.

Gupta, B. S., Jelle, B. P., Hovde, P. J., Rüther, P., 2011: Studies of wooden cladding materials degradation by spectroscopy. Proceedings of the Institution of Civil Engineers – Construction Materials, 164:329–340.

Hirche, M., 2014: Wood Weathering as Design Option. Dissertation, Norwegian University of Science and Technology, 272 p.

Hon, D. N. S.; Shiraishi, N., 2001c: Wood and cellulosic chemistry. 2nd ed., rev. And expanded. New York: Marcel Dekker, 928 p.

Hrapková, L., Rychtář, J., Veselý, V., 2012: Fasádní obklady dřevěné a z materiálů na bázi dřeva. Stavební partner, 1:1–12.

Ingo, G., 2011: Dřevěné fasády: materiály, návrhy, realizace. Praha, Grada, 136 p.

Kržišnik, D., Lesar, B., Thaler, N., Humar, M., 2018: Micro and materiál climate monitoring in wooden buildings in sub-Alpine environments. Available online: https://www.sciencedirect.com/science/article/pii/S0950061818301417 (accessed on 20 April 2020).

Lesar, B., Humar, M., Kržišnik, D., Thaler, N., Žlahtič, M., 2016: Performance of façade elements made of five different thermally modified wood species on model house in Ljubljana. In: Proceedings of the World Conference on Timber Engineering, Vienna, 22–25 August 2016.

Mohebby, B., Saei, A. M., 2015: Effects of geographical directions and climatological parameters on natural weathering of fir wood. Construction and Building Materials, 94:684–690.

Müller, U., Rätzsch, M., Schwanninger, M., Steiner, M., Zöbl, H., 2003: Yellowing and IR-changes of spruce wood as result of UV-irradiation. Journal of Photochemistry and Photobiology B: Biology, 69:97–105.

Musil, I., Hamerník, J., 2007: Jehličnaté dřeviny – Lesnická dendrologie I. Praha, Academia, 352 p.

Oberhofnerová, E., Pánek, M., 2016: Surface wetting of selected wood species by water during initial stages of weathering. Wood Research, 61:545–552.

Oberhofnerová, E., Pánek, M., García-Cimarras, A., 2017: The effect of natural weathering on untreated wood surface. Maderas: Ciencia y Tecnologia, 19:173–184.

Pandey, K. K., 2005: A note on the influence of extractives on the photo-discoloration and photo-degradation of wood. Polymer Degradation and Stability, 87:375–379.

Pastore, T. C. M., Santos, K. O., Rubim, J. C., 2004: A spectrocolorimetric study on the effect of ultraviolet irradiation of four tropical hardwoods. Bioresource Technology, 93:37–42.

Požgaj, A., Chovanec, D., Kurjatko, S., Babiak, M., 1993: Štruktúra a vlastnosti dreva. Bratislava, Príroda, 485 p.

Reinprecht, L., 2012: Ochrana dreva. Zvolen, Technical University in Zvolen, 453 p.

Reinprecht, L., 2016: Wood Deterioration, Protection and Maintenance; John Wiley & Sons, Chichester, UK, 376 p.

Reinprecht, L., Vidholdová, Z., 2008: Mould resistance, water resistance and mechanical properties of OHT-thermowoods. Sustainability through New Technologies for Enhanced Wood Durability: Socio-economic perspectives of treated wood for the common European market, p. 159–165.

Sandak, A., Sandak, J., 2017: Prediction of service life – does aesthetic matter? In: Proceedings IRG Annual Meeting, Ghent, Belgium, 4–8 June 2017. Available online: https://www.researchgate.net/publication/318212393 (accessed on 23 April 2020).

Sehlstedt-Persson, M., 2003: Color responses to heat-treatment of extractives and sap from pine and spruce. In: Proceedings of the 8th IUFRO International Wood Drying Conference: Improvement and Innovation in Wood Drying: A Major Issue for a Renewable Material, Brasov, Romania, 24–29 August 2003; Faculty of Wood Industry, Transilvania University of Brasov, p. 459–464.

Sohngen, B., Mendelsohn, R., Sedjo, R., 1999: Forest management, conservation, and global timber markets. American Journal of Agricultural Economics, 81:1–13.

Teacà, C. A., Rosu, D., Bodirlau, R., Rosu, L., 2013: Structural changes in wood under artificial UV light irradiation determined by FTIR spectroscopy and color measurements–A brief review. BioResources, 8:1478–1507.

Temiz, A., Yildiz, U. C., Aydin, I., Eikenes, M., Alfredsen, G., 2005: Surface roughness and color characteristics of wood treated with preservatives after accelerated weathering test. Applied Surface Science, 250:35–42.

Tolvaj, L., Faix, O., 1995: Artificial ageing of wood monitored by DRIFT spectroscopy and CIE L* a* b* color measurements. 1. Effect of UV light. 113 Holzforschung-International Journal of the Biology, Chemistry, Physics and Technology of Wood, 49:397–404.

Wagenführ, R., 2003: Dřevo – obrazový lexikon. No: 1, Příbram, Tiskárny Pbtisk Příbram, 348 p.

Williams, R. S., Feist, W. C., 1999: Water repellents and water-repellent preservatives for wood. Forest Products Laboratory, 12 p.

Williams, R. S., Knaebe, M. T., Feist, W. C., 2007: Erosion rates of wood during natural weathering. Part II, Earlywood and latewood erosion rates. Wood and Fiber Science, 33:43–49.

Williams, R. S., 2005: Handbook of wood chemistry and wood composites. In: R. M. Rowell (ed.): Boca Raton, Fla: CRC, 703 p.

Other sources

CIE, 1986: Colorimetry. 2nd Edition, CIE Pub. No. 15.2, Commission Internationale de l´Eclairage, Vienna, 74 p.

EN 335 (2013): Durability of wood and wood-based products – Use classes: definitions, application to solid wood and wood-based products. European Committee for Standardisation (CEN), Brussels, Belgium.

EN 350 (2016). Durability of wood and wood-based products – Testing and classification of the durability to biological agents of wood and wood-based materials, European Committee for Standardization, Brussels, Belgium.

EN 927–3 (2006). Paints and varnishes. Coating materials and coating system for exterior wood, Part 3: Natural weathering test, European Committee for Standardization, Brussels, Belgium.

EN ISO 2813 (2014). Paints and Varnishes - Determination of Gloss Value at 20 Degrees, 60 Degrees and 85 Degrees, International Organization for Standardization: Geneva, Switzerland.

EN ISO 4628 (2003). Paints and varnishes. Evaluation of degradation of coatings. Designation of quantity and size of defects, and of intensity of uniform changes in appearance, European Committee for Standardization, Brussels, Belgium.