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DRYING CHARACTERISTICS OF WOOD OF INVASIVE TREE SPECIES GROWING IN AN URBAN ENVIRONMENT

DOLOČANJE SUŠILNIH KARAKTERISTIK LESA INVAZIVNIH DREVESNIH VRST RASTOČIH V URBANEM OKOLJU

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Abstract / Izvleček

Abstract: *Non-native tree species are increasingly growing in urban environments, where they are exposed to cultivation and pruning measures, and in many cases their growth becomes uncontrolled, even invasive. In such cases the structure of the wood is more heterogeneous, with more tyloses, discolorations and decay, and higher moisture content. The drying of such wood is more demanding and cannot rely on the standard drying schedules. Therefore, the drying kinetics of the boards (thickness 22 mm, 28 mm and 46 mm) of three wood species (black locust –* Robinia pseudoacacia*; box elder –* Acer negundo *and horse chestnut –* Aesculus hippocastanum*) were analysed at 20 °C and 40 °C. Additionally, the drying quality was assessed by determining the moisture content gradient, drying stresses and presence of typical drying defects. In the drying tests the moisture content gradients were relatively low in all species, so no high drying stresses were generated. Due to the expected high risk of collapse, careful drying of green maple was needed, to prevent board twisting when a pronounced number of knots and greater fibre deviation occurred. Half-drying times indicated the longer drying of thicker black locust boards, and very careful drying of box elder. We confirmed the usability of the half-drying time to compare the drying kinetics of different wood species and assortments.*

Keywords: *invasive wood species, wood, permeability, diffusivity, drying rate, drying quality*

Izvleček: *V vrtovih in parkih se zaradi oblik in privlačnega videza vse pogosteje razširjajo neavtohtone drevesne vrste, ki so podrejene posebnim gojitvenim in obrezovalnim ukrepom. Pogosto lahko postane njihova širitev nekontrolirana, celo invazivna. V primeru takih dreves je struktura lesa bolj heterogena, les je bolj verjetno otiljen, diskoloriran in okužen ter ima višjo vlažnost. Sušenje takšnega lesa je težavnejše in ne omogoča uporabe standardnih sušilnih programov. Raziskali smo kinetiko sušenja treh lesnih vrst (robinije –* Robinia pseudoacacia*; amerikanskega javorja –* Acer negundo *in divjega kostanja –* Aesculus hippocastanum*). Sušili smo deske debelin 22 mm, 28 mm in 46 mm pri 20 °C in 40 °C. Ob tem smo spremljali kakovost sušenja. Ocenjevali smo vlažnostni gradient, sušilne napetosti in pojav značilnih napak pri sušenju. Pri sušilnih preizkušancih so bili vlažnostni gradienti pri vseh lesnih vrstah razmeroma nizki, zato nismo zabeležili visokih sušilnih napetosti. Raziskave so pokazale, da je zaradi ugotovljene nevarnosti kolapsa potrebno previdno sušenje lesa svežega amerikanskega javorja, da se prepreči krivljenje desk, zlasti ob prisotnosti številnih grč in večjem odstopanju poteka lesnih vlaken. Polovični časi sušenja so nakazovali daljše sušenje debelejših preizkušancev robinije in zelo previdno sušenje javorja. Potrdili smo uporabnost kinetike polovičnega časa sušenja različnih vrst in debelin lesa.*

Ključne besede: *invazivne lesne vrste, les, permeabilnost, difuzivnost, hitrost sušenja, kakovost sušenja*

1 INTRODUCTION

1 UVOD

Their attractive appearance, great adaptability and flexibility to growth conditions, and variations of tree shapes are the reasons that more and more tree species are spreading from their natural environments to non-native habitats. They are most commonly found in parks, gardens and urban environments. In gardens and parks, trees are subjected to specific cultivation and pruning measures, and in many cases their growth becomes uncontrolled. Therefore, we a consider them invasive species.

As these trees do not grow in forest stands they have the characteristics of freestanding trees, as also often found in urban areas. The features are evident in the crown length, which extends from the top to the ground of the tree, the trunk is of conical in shape, the branches and knots are present through-

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out the entire tree height (Zobel & Buijtenen, 1989**;** Ramagea et al., 2017). In addition, the trunk contains a greater proportion of juvenile wood, the amount of sapwood is larger and the growth rings are wider. Due to the characteristic growth conditions and human activity affecting tree growth, the structure of the wood is usually very heterogeneous and deviates from that which is typical for forest trees in a closed stand; the proportion of juvenile wood is higher; the response of living trees to external injuries is accompanied by compartmentalization processes with an emerging amount of discoloured wood (Torelli, 1974), and there are more knots and fibre deviations (Dinwoodie, 2000).

Frequent human interventions to form the tree shape and greater exposure to a wide variety of mechanical damage mean that wood tissues respond more intensively with abiotic, physiological and biochemical reactions (Racz et al., 1961; Nečesany, 1969; Koch et al., 2000; Koch et al., 2003). In areas around tree wounds, mostly phenolic substances are accumulated in the lumens of parenchymal cells. In less-filled lumens, free water is replaced by air, which causes oxidation processes, condensation, and polymerization of the accumulated substances in parenchyma cells (Nečesany, 1966; Torelli, 1984). The resulting products are less soluble, while enzymes could induce oxidative coloration, i.e. discoloured wood (Bosshard, 1965, 1967; Kučera, 1971; Bauch, 1984). The formation and development of staining is also determined by the ratio of free water to gases in the lumens, which affect the vitality of parenchyma cells (Bosshard, 1965; Sachsee, 1965).

The response of trees to frequent mechanical damage is manifested by an atypical distribution of moisture content, not only by the sporadic occurrence of wet pockets in the radial direction, but also by greater variation in moisture content along the tree axis. The drastic increase of tyloses, pit aspiration, more biologically infected wood and lighter wood with poor mechanical properties makes drying of this wood very demanding (Gorišek et al., 2008; Gorišek & Straže, 2009), so we cannot rely on the standard drying schedules (Plavčak et al., 2018).

Sapwood, which is involved in water transport, has a high amount of water, which is highly dependent on the leaf surface and water requirements of the tree (Tyree & Zimmermann, 2002). The ratio of leaf area to sapwood area also depends on the availability of water in the soil, the average relative air humidity, the age of the tree, the vitality of the tree, the amount of ions and nutrients in the soil, and the height of the tree (Wullschleger et al., 1998). With tree growth the capillary flow moves more and more toward the periphery of the trunk, and therefore the core loses its transport function which results in the loss of free water; however, the moisture content still remains above the fibre saturation point (FSP). The discoloured wood is often associated with increased moisture content and biological infection (Torelli, 1974).

Permeability of the wood has an important role in drying and impregnation processes as it determines the ease of water flow through a porous structure (Walker, 2006). Considering Darcy's law (eq. 1), the volumetric flow rate is directly proportional to the applied pressure difference, while gas compressibility is also taken into account in gas flow (eq. 2) (Siau, 1971, 1984).

$$k = \frac{V}{t}\frac{\eta L}{A \Delta P} \tag{1}$$

$$k_g = \frac{V}{t}\frac{\eta L P}{A \Delta P P_a} \tag{2}$$

Designation:
k, k_g coefficient of liquid or gas permeability [m^3/m Pa s],
V/t volumetric flow [m^3/s],
L length of the specimen in the flow direction [m],
A cross section area of specimen [m^2],
ΔP pressure difference [Pa],
η dynamic viscosity [Pa s],
P_a average pressure [Pa],
P pressure at which the liquid flow is determined [Pa].

Despite several limiting factors, Darcy's law remains the dominant starting point for studying the capillary flow of free water in wood. The movement of free water is certainly not limited with the size of cell lumens. The passages through the pits in the cell wall have a significantly more important role. Moreover, the inhomogeneity and incompressibility of the fluid, as well as independence from the specimen length and certain other restrictions, have been taken into consideration (Bramhall, 1971; Siau, 1971; Kumar, 1981). During liquid flow the flux effectiveness may be affected by the appearance of air bubbles, plugged pores by particles and/or the occurrence of the slip effect (Resh & Ecklund, 1964; Comstock, 1967; Sabastian et al., 1973; Petty, 1975; Kumar, 1981; Salin, 2008).

In sapwood the pits are relatively open so water can flow smoothly from one lumen to another. Secondary processes of heartwood formation and compartmentalization processes after tree wounding cause aspiration of boarded pits and the formation of tyloses. In this way many pits between adjacent lumens are closed (Hansmann et al., 2002). In such cases, the free flow of capillary water is rather difficult, so the transport of water in the wood is limited by a much less efficient diffusion flow, which is otherwise characteristic of the transfer of bound water.

The capillary flow of free water from the core to the surface must be closely related to the evaporation rate into the surroundings, and therefore the constant drying rate is established which can be found at carefully dried low density or highly permeable wood species. The surface of less permeable wood dries quickly below the FSP, so often a considerable amount of free water remains trapped in the core. Further transport of water takes place only with a less efficient diffusion flow (Avramidis, 2008).

In the drying practice, more attention is paid to the diffusion flow of bound water, which is much slower than the capillary flow. Optimization of this drying interval results in greater time- and energy savings. When wood dries under the FSP, many physical, mechanical and chemical properties change dramatically, which significantly affects its final quality.

Fick's second law of diffusion usually represents the starting point to study the flow of bound water based on the molecular flow under the influence of a concentration gradient (eq. 3) (Crank, 1964).

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \tag{3}$$

Designation:
D diffusion coefficient [m^2/s],
∂c/∂t bound water flow, i.e. time derivative of concentration of bound water [kg/s],
$\partial^2c/\partial x^2$ second derivative of bound water concentration [kg/m^2].

Much research energy has been expended with the aim to bring the solution of Fick's law as close to actual water flow as possible (Avramidis, 2008). There have been also many arguments about the effect of different factors that the law doesn't take into account. The discussion is related to driving potential (Hunter, 1993; Bramhall, 1976), nonisotermal diffusion (Siau & Babiak, 1983; Siau & Jin, 1985; Siau et al., 1986; Avramidis et al., 1987b), influence of moisture content (Stamm, 1967; Skaar, 1988; Choong, 1963, 1965; Rosen, 1976; Avramidis & Siau, 1987a; Wadso, 1994; Siau, 1984), surface phenomena (Rosen, 1978; Avramidis & Siau, 1987b; Cai & Avramidis, 1993; Siau & Avramidis, 1996; Wadso 1994), sorption hysteresis or history of speciment (Comstock, 1963; Siau, 1984; Salin, 2010) and the thickness of specimens (Remond et al., 2005; Straže & Gorišek, 2009)

The aim of this study was to investigate the wood of three tree species, black locust, horse chestnut and box elder, to determine their relevant drying characteristics. In addition, we determined the distribution of water in green wood, the types of water transport in wood, and the permeability and diffusivity of wood, which are of particular importance to select optimal drying schedules.

2 MATERIAL AND METHODS
2 MATERIAL IN METODE

For this study we selected: black locust (*Robinia pseudoacacia* L.), horse chestnut (*Aesculus hippocastanum* L.) and box elder (*Acer negundo* L.), which are considered invasive alien species present in sufficient quantity for potential wood utilization. We chose this selection because these wood species have very different densities, initial moisture contents (MC) and distributions, the presence of sapwood and heartwood, as well as discolorations and infections in standing trees.

Material for the drying experiments was selected in a park and three trees of each species were collected for examination (Table 1). Then, central radial boards from sawn timber were selected. A part of each central board was cut in 5 to 10 mm thick strips on which mean distance from the pith, mass and volume in green and oven dry state were measured for subsequent determination of the radial density and moisture content profile (Figure 1).

Drying kinetics were investigated on elements of three thicknesses (22 mm, 28 mm and 46 mm), and the same width (80 mm) and length (600 mm). Six samples were randomly selected for each experiment (Figure 2).

Table 1. Number of growth rings and diameter of the studied trees at the sampling point of the specimens.
Preglednica 1. Število branik in premeri proučenih vzorčnih dreves na lokaciji vzorčenja.

Wood species / Lesne vrste		No. of tree / Št. drevesa	No. of growth rings at the sampling / Št. branik na vzorcu	Diameter of tree / Premer drevesa [mm]
Robinia pseudoacacia	RoPs	1	51	149
Black locust /		2	85	198
Robinija		3	54	207
Aesculus hippocastanum	AeHi	1	58	289
Horse chestnut /		2	59	289
Divji kostanj		3	125	256
Acer negundo	AcNe	1	86	229
Box elder /		2	54	189
Amerikanski javor		3	62	230

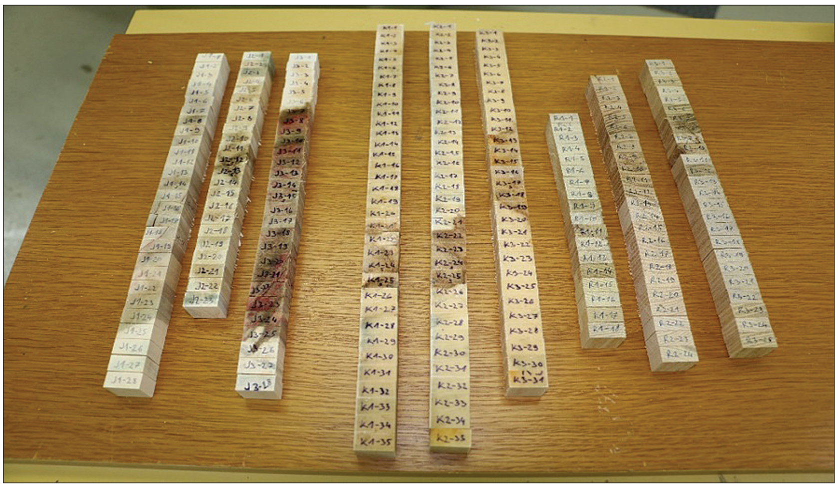


Figure 1. Samples cut from the central board to determine the radial density and moisture content profile (from periphery through pith to periphery of the stem) of box elder, horse chestnut and black locust.
Slika 1. Preizkušanci iz centralne deske za določanje radialnega gostotnega in vlažnostnega profila (od periferije preko stržena do periferije debla) za amerikanski javor, divji kostanj in robinijo.

Figure 2. Experimental drying chamber with wood samples.
Slika 2. Eksperimentalna sušilna komora s preizkušanci.

Figure 3. Samples for determination of the moisture content gradient and drying stresses.
Slika 3. Vzorčenje za določanje vlažnostnega gradienta in sušilnih napetosti.

Drying was carried out in controlled condition at two temperatures (20 °C and 40 °C) with a constant drying gradient. Every 24 to 48 hours each sample was weighed and three times during the process the moisture content gradient and drying stresses were determined (Figure 3).

The drying kinetics were studied by constructing a drying curve, which was divided into a constant drying rate section and a diffusion drying part. The drying rate of green wood was determined from the initial slope of the drying curve. Linearity was assessed with regard to the moisture content where a constant drying rate prevailed.

Due to the highly demanding drying of discoloured wood of box elder, we compared the drying rate with the permeability of each category of wood, i.e. sapwood, discoloured wood and heartwood. The gas permeability was determined in all anatomical directions on oriented specimens with a cross-sectional area of 15 mm × 15 mm, the length of the specimens was 15 mm when measured in the longitudinal direction and 5 mm measured in the tangential or radial directions. The coefficient of gas permeability was calculated from the derivation of Darcy's law for gases (eq. 2).

The diffusivity of wood for bound water was determined from a non-stationary experiment and by the analytical solution of the Fick's second law (eq. 3) for mass transfer in a thin plate with constant transfer coefficients. By introducing the dimensionless mass change (eq. 4) and conditions of constant diffusion coefficient, homogeneous initial distribution of moisture content and symmetrical distribution of moisture content through the cross section of the sample, the diffusivity is expressed with equation 5. Additionally, the diffusion coefficient can also be determined from the half-drying time (eq. 6).

$$E = \frac{m(t) - m_f}{m_i - m_f} = \frac{4}{\sqrt{\pi}} \sqrt{\frac{Dt}{l^2}} \tag{4}$$

$$D = \frac{\pi l^2}{4} \left(\frac{dE}{d\sqrt{t}} \right)^2 \tag{5}$$

$$D = \frac{1}{\pi^2} ln \frac{\pi^2}{16} \left(\frac{l^2}{t_{1/2}} \right) = 0.049 \left(\frac{l^2}{t_{1/2}} \right) \tag{6}$$

Designation:

- E dimensionless mass [],
- $m(t)$ mass at time t [g],
- m_i, m_f initial ($_i$) and final ($_f$) mass [g],
- D coefficient of diffusivity [m²/s],
- t time [s],
- $t_{1/2}$ half drying time [s],
- l half thickness of the specimen [m].

3 RESULTS AND DISCUSSION
3 REZULTATI IN RAZPRAVA

At the beginning of the drying process the sawn timber contained approximately the same amount of water as in the living tree. Relatively low moisture content was detected in the case of black locust (Figure 4), which was partly the result of a pre-dried stem at the time of tree felling. Regarding the definition of moisture content (MC), due to the high density of the black locust wood the amount of mainly bound water was substantially higher than in the lighter woods. As expected, the MC of sapwood was about two times higher than that of the heartwood.

Low density horse chestnut proved to have high and relatively evenly distributed water across the entire cross section. As the horse chestnut does not form heartwood, sporadically arranged wet pockets occasionally appeared as a result of tree response to mechanical injury. Because of their slightly darker appearance, wet pockets could be noticed visually.

While in the horse chestnut stem we did not detect a high difference of MC between sapwood and discoloured wood, greater differences in MC could be observed in box elder (Figure 4). Different amounts of water are associated with the visual assessment of colour, and specifically distinct and attractive red discoloration areas had slightly lower MC content compared to the areas of intense brown shades in which the infection was already widespread, as reported in a previous study (Plavčak, 2018). Unstained wood was characterized by a lower MC, which could be partly also ascribed rapid drying of very permeable sapwood without discolouration.

The drying rate, calculated from the slope of the drying curve in the first period, could serve as an indicator of the ease of drying of green wood. It is believed that a constant drying rate is achieved when free water is maintained at the surface. For all tree species studied, lower drying rates were determined in boards of greater thickness (Table 2). The constant rate of drying was reached only in the thinner elements, whereas in the thicker ones the drying rate decreased immediately from the beginning of the procedure. It is believed that in this context the moisture transport in the dried material was insufficient to keep the surface moisture content above the FSP (Youngman et al., 1999; Hukka & Oksanen, 1999; Tremblay et al., 2000; Perre & Karimi, 2002).

The slowest drying was determined in the black locust at both temperature levels (Table 2). Due to low initial moisture content, the constant

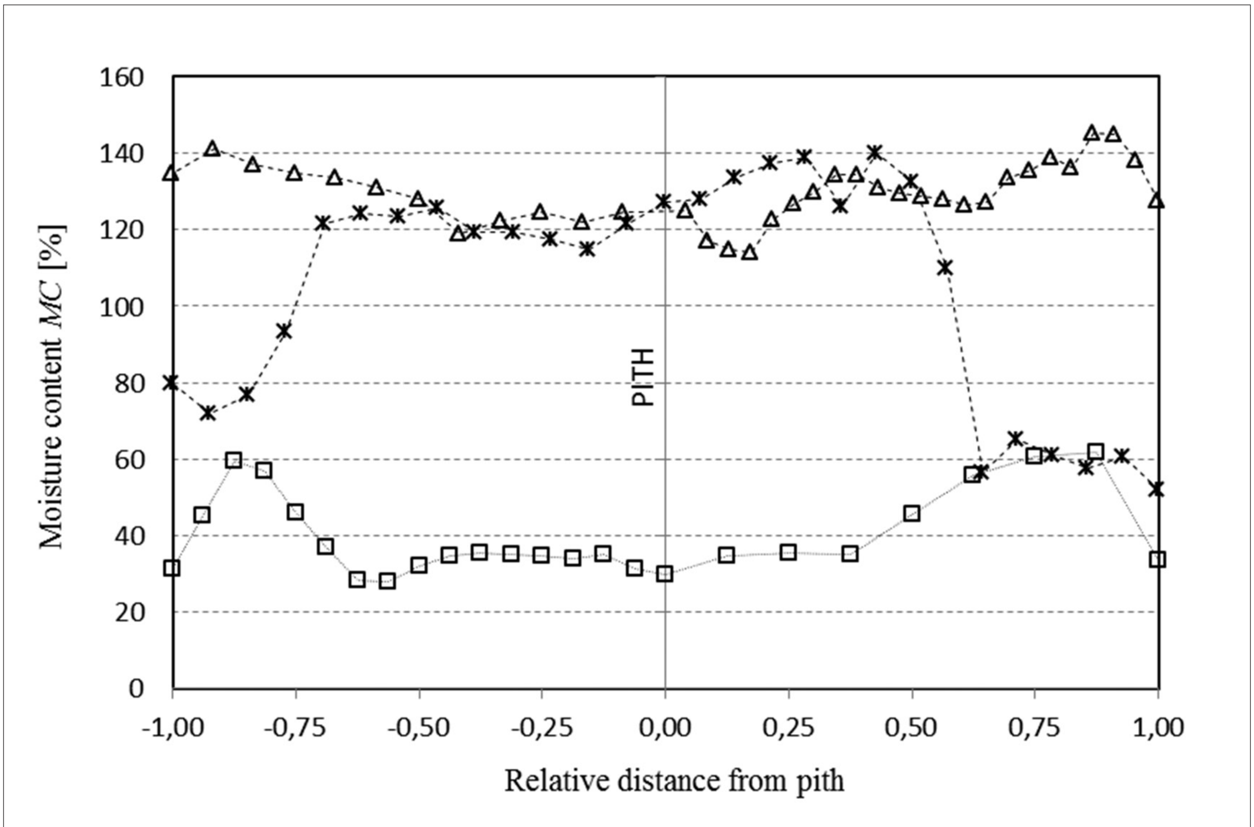


Figure 4. Radial moisture content distribution in the stems of (□) black locust, (Δ) horse chestnut and (×) box elder.
Slika 4. Radialna porazdelitev vlažnosti v drevesu: (□) robinija, (Δ) divji kostanj in (×) amerikanski javor.

drying rate period was very short, so the diffusion flow prevailed throughout most of the drying process. As expected, drying was faster at higher temperatures.

Drying of green horse chestnut and box elder wood was especially efficient at higher temperatures. Despite rapid drying, great care had to be taken when discoloured wood was present, as the high regular shrinkage of box elder wood in the discoloured region is often accompanied by collapse of the tissue (Merela et al., 2019). Collapse occurs if the capillary tension, which is strongly dependent on wood permeability, exceeds the compression strength of wood. The comparison of gas permeability (eq. 4) (Gorišek & Straže, 2009) showed that the infected wood has the lowest conductivity, being 3.5 times less than sapwood and 1.3 times less than only discoloured wood (Table 3). The risk of collapse is more pronounced in infected wood because the biologically degraded cell walls cause greatly reduced strength. Due to its lower strength, drying of such wood at higher temperatures is more risky.

Table 2. The average value (bold) and standard deviation of the drying rate during the first drying period for black locust, box elder and horse chestnut for three thicknesses and at two temperature levels.
Preglednica 2. Povprečna vrednost (poudarjeno) in standardni odklon hitrosti sušenja v prvi fazi sušenja za robinijo, divji kostanj in ameriški javor pri treh debelinah in dveh temperaturah.

Thickness / Debelina [mm]	Drying rate within 1. period [%/day] / Sušenje v prvi fazi [%/dan]					
	T = 20 °C			T = 40 °C		
	Black locust / robinija	Horse chestnut / divji kostanj	Box elder / amerikanski javor	Black locust / robinija	Horse chestnut / divji kostanj	Box elder / amerikanski javor
22	**0.62**	**1.31**	**1.36**	**1.41**	**5.94**	**6.51**
	0.055	0.042	0.047	0.440	1.805	1.581
28	**0.47**	**1.69**	**1.43**	**0.69**	**4.92**	**9.04**
	0.042	0.311	0.172	0.180	0.992	2.214
46	**0.34**	**1.05**		**0.54**	**4.70**	
	0.065	0.151		0.299	1.929	

Table 3. Coefficients of gas permeability for sapwood, infected wood and discoloured wood of box elder.
Preglednica 3. Koeficient plinske permeabilnosti beljave, okuženega lesa in rdeče obarvanega diskoloriranega lesa amerikanskega javorja.

	Sapwood / Beljava	Infected wood / Okužen les	Discoloured wood / Diskoloriran les
	Coefficient of permeability / Koeficient permeabilnosti k_g [m³/(m Pa s)]		
Average	**$1.59 \cdot 10^{-7}$**	**$4.53 \cdot 10^{-8}$**	**$5.53 \cdot 10^{-8}$**
St. deviation	$7.24 \cdot 10^{-8}$	$1.49 \cdot 10^{-8}$	$1.41 \cdot 10^{-8}$
c.v. [%]	45.5	32.9	25.5

Despite the fact that, especially in the case of lighter wood, the quantity of free water is much higher than the quantity of bound water, the time and also energy consumption primarily depend on the diffusion characteristics of wood and its ability to transport the bound water and water vapour. Therefore, the coefficient of moisture diffusion is the most important factor affecting the drying rate.

In order to determine the diffusion characteristics, we placed wood specimens in a controlled climate chamber with constant temperature and relative humidity and monitored their change in weight

Table 4. The bound water diffusion coefficients for black locust, box elder and horse chestnut at two temperature levels.
Preglednica 4. Koeficient difuzivnosti vezane vode za les robinije, divjega kostanja in amerikanskega javorja pri dveh temperaturah.

	Diffusion coefficient / Difuzijski koeficient D [10^{-9} m^2/s]					
	Black locust / robinija		Horse chestnut / divji kostanj		Box elder / amerikanski javor	
Thickness / Debelina [mm]	T = 20 °C	T = 40 °C	T = 20 °C	T = 40 °C	T = 20 °C	T = 40 °C
46	0.39	0.43	0.83	0.96	0.42	0.99
28	0.73	0.83	1.84	2.03	0.85	1.98
22	2.84	2.73			3.51	5.24

change, and thus moisture content, as a function of time until equilibrium was achieved. From the drying curves (Figure 5) the coefficients of diffusivity and half-drying times were calculated for all tree species, thicknesses and temperature levels (eq. 5 and eq. 7).

The moisture transport in wood below the FSP is governed by more mechanisms, as follows: as bound water diffusion in the cell wall, as water vapour diffusion in the cell lumen as well as surface emission coefficient. Since bound water diffusion represents the greatest resistance, it also has a decisive effect on the apparent diffusion coefficient, so there is close correlation with the porosity or density of wood, as also confirmed by our measurements (Table 4). As expected, the denser black locust wood had the lowest value of diffusivity, whereas the lighter horse chestnut and box elder performed better concerning the movement of bound water.

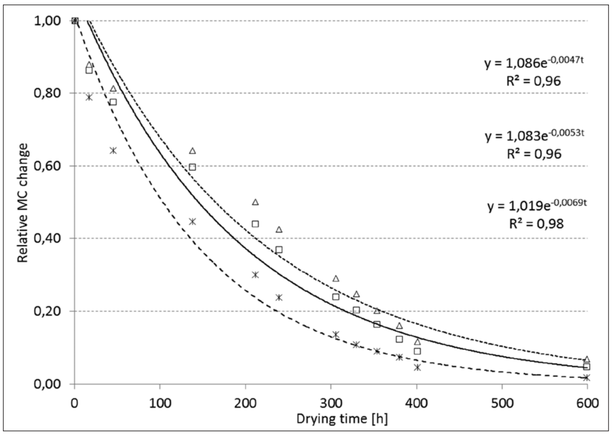
The bound-water diffusion coefficients were affected positively by the increase in temperature. The most pronounced influence of temperature was observed in box elder, while the effect was lower in the other two species. A higher coefficient of diffusivity was found for thinner elements, which could be attributed to stress relaxation.

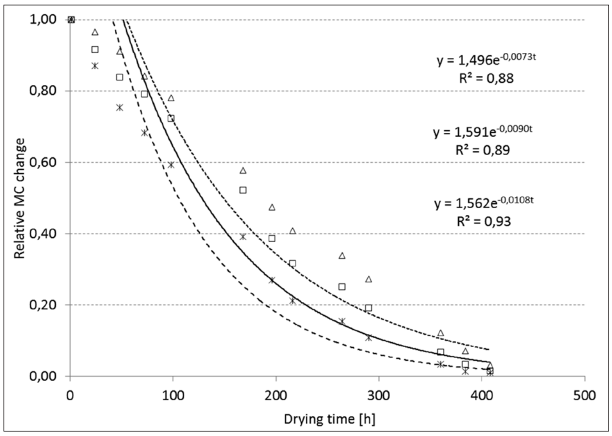
In terms of practical application, the expression of flow capability with half-drying time seems to be more useful (Table 5), and additionally supports the results given for the diffusion coefficient. We confirmed the reciprocal relationship between the two variables.

Table 5. The average value (bold) and standard deviation of half drying time for black locust, box elder and horse chestnut for three thicknesses at two temperature levels.
Preglednica 5. Povprečna vrednost (poudarjeno) in standardni odklon polovičnega časa sušenja robinije, divjega kostanja in amerikanskega javorja pri treh debelinah in dveh temperaturah.

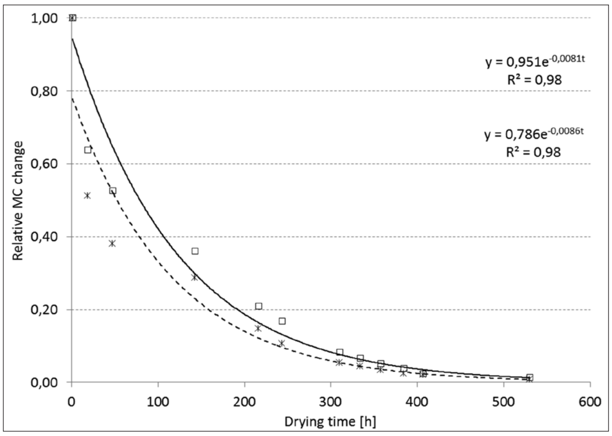
	Half-drying time / Polovični čas sušenja $t_{1/2}$[h]					
	Black locust / robinija		Horse chestnut / divji kostanj		Box elder / amerikanski javor	
Thickness / Debelina [mm]	T = 20 °C	T = 40 °C	T = 20 °C	T = 40 °C	T = 20 °C	T = 40 °C
46	**165** (10.6)	**150** (9.1)	**79** (9.2)	**69** (8.4)	**155** (10.9)	**66** (8.2)
28	**146** (10.7)	**129** (8.8)	**58** (6.9)	**53** (7.2)	**125** (11.9)	**54** (6.1)
22	**103** (9.6)	**95** (9.1)			**82** (9.1)	**55** (6.2)

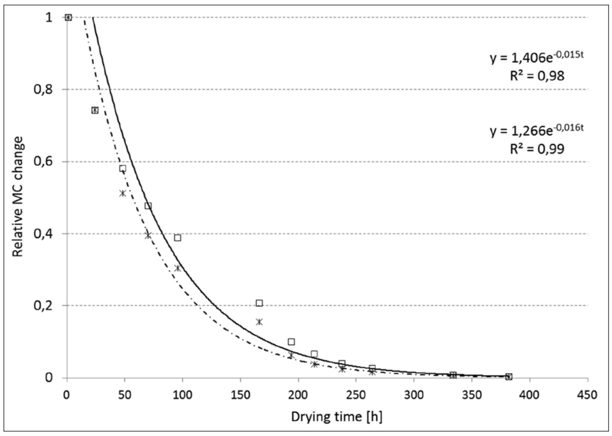
Black locust - *Robinia pseudoacacia*



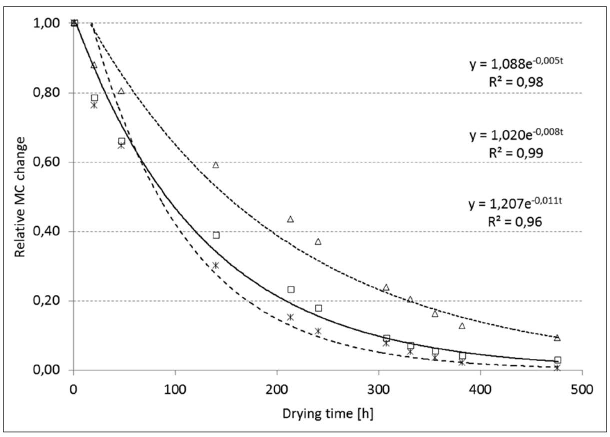


Horse chestnut - *Aesculus hippocastanum*





Box elder - *Acer negundo*



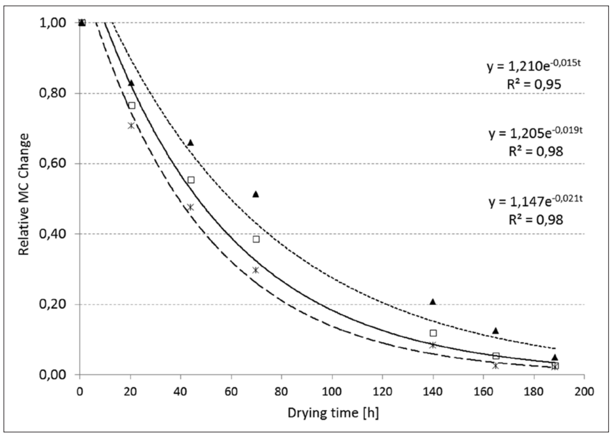


Figure 5. Drying curve of investigated wood species of three thicknesses (22 mm, 28 mm and 46 mm) at temperatures of 20 °C (left) and 40 °C (right).

Slika 5. Sušilna krivulja raziskanih lesnih vrst za tri debeline (22 mm, 28 mm in 46 mm) pri temperaturah 20 °C (levo) in 40 °C (desno).

Figure 6. Extreme collapse of infected tissue of box elder.
Slika 6. Izrazito krčenje (kolaps) okuženega tkiva lesa amerikanskega javorja.

Table 6. Moisture content gradient in black locust, box elder and horse chestnut for three thicknesses at two temperature levels.
Preglednica 6. Vlažnostni gradient v lesu robinije, divjega kostanja in amerikanskega javorja pri treh debelinah in dveh temperaturah.

Thickness / Debelina [mm]	Black locust / robinija		Horse chestnut / divji kostanj		Box elder / amerikanski javor	
	MC gradient / Vlažnostni gradient [%/cm]		MC gradient / Vlažnostni gradient [%/cm]		MC gradient / Vlažnostni gradient [%/cm]	
	T = 20 °C	T = 40 °C	T = 20 °C	T = 40 °C	T = 20 °C	T = 40 °C
46	0.19	0.91	0.88	1.23	0.27	0.88
28	1.27	0.41	0.23	0.49	0.41	2.77
22	2.61	0.97			1.54	4.19

The final control of the drying quality showed that, in accordance with the determined diffusion characteristics, the extent of moisture gradients (Table 6) and the generation of drying stresses can be predicted. The minor tensions in the black locust in particular are a reflection of its low shrinkage. Due to the tendency to collapse, careful drying of box elder is required above the FSP (Figure 6).

4 CONCLUSIONS
4 ZAKLJUČKI

In black locust, the radial distribution of moisture content in green logs had a pattern which is typical for species with heartwood. In box elder, the green moisture distribution varied significantly with randomly distributed areas of a very high level of moisture content, accompanied by discoloration and biological infection. Horse chestnut has relatively homogenously distributed and high green moisture content.

The low bound-water diffusion coefficients and long half-drying times showed that black locust requires very slow and prolonged drying, as also confirmed in practice (Merela et al., 2019). The diffusivity of horse chestnut and box elder proved to be moderate and therefore did not negatively affect the drying. However, the trapped free water in wet pockets (if present) should be considered.

Careful drying of discoloured wood of box elder is required above the FSP.

Considering the drying gradient and hardening after drying no special problems are expected when drying black locust, box elder and horse chestnut wood.

5 SUMMARY
5 POVZETEK

Raznovrstne oblike in privlačen videz so vzrok, da vse več drevesnih vrst razširjamo po neavtohtonih rastiščih, kjer jih najpogosteje zasledimo v parkih, vrtovih in urbanem okolju. V takih okoljih so drevesa podrejena posebnim gojitvenim in obrezovalnim ukrepom, v več primerih pa njihovo razraščanje postane nekontrolirano in postanejo invazivne vrste. Zaradi značilnih rastnih pogojev in človeških posegov je zgradba lesa takih dreves zelo heterogena in odstopa od tiste, ki je značilna

za drevesa v naravnih sestojih: več je juvenilnega lesa, nastaja diskoloriran les zaradi odzivov dreves na poškodovanja. Več je vraslih grč in odklonov vlaken. Odziv dreves na pogosta poškodovanja se kaže v močnem otiljenju pri listavcih in v aspiraciji obokanih pikenj pri iglavcih. Posledica je lahko netipičen razpored vlažnosti, pojav mokrin in večja variabilnost vlažnosti po višini drevesa. Sušenje pogosto nekoliko redkejšega lesa s slabšimi mehanskimi lastnostmi in s pogostimi biološkimi okužbami je zelo težavno, zato se v sušilnem procesu ne moremo zanesti na standardne sušilne programe. Zaradi slabe permeabilnosti lesa teh vrst se pri sušenju pojavijo težave že v prvi fazi, več težav je tudi pri impregnaciji lesa.

Za raziskave smo izbrali tri drevesne vrste, ki bi jih zaradi razpoložljivih količin lesa lahko gospodarsko izkoriščali. To so: robinija - *Robinia pseudoacacia*; amerikanski javor – *Acer negundo* in divji kostanj – *Aesculus hippocastanum*. Za vse vrste smo določili radialni razpored vlažnosti na vzorcih svežega lesa. Vzorce svežega lesa treh debelin (22 mm, 28 mm in 46 mm) smo sušili pri konstantni ostrini sušenja pri dveh temperaturah (20 °C in 40 °C). Za vsako lesno vrsto, debelino in temperaturo smo za sušenje izbrali šest preizkušancev. Kakovost sušenja smo vzporedno preverjali z določevanjem vlažnostnega gradienta, merjenjem sušilnih napetosti in zaznavanjem tipičnih sušilnih napak veženja, razpok, itd. (Slika 2).

Iz začetnega linearnega dela sušilne krivulje smo izračunali hitrost sušenja, iz relativne spremembe mase pa smo izračunali difuzijske koeficiente in polovične uravnovesne čase. Zaradi intenzivnih obarvanj in okužb smo pri javorju izmerili tudi prevodnost beljave, rdeče obarvanega diskoloriranega lesa in rjavega že okuženega lesa.

Radialni vlažnostni profil pri robiniji je bil sicer tipičen (Slika 4), z višjo vlažnostjo beljave in nižjo vlažnostjo jedrovine, vendar še vedno nad točko nasičenja celičnih sten. Nekoliko nižje vrednosti od pričakovanih pripisujemo temu, da so se po poseku debla že nekoliko osušila. Za divji kostanj je bila značilna visoka vlažnost po celotnem prečnem prerezu, javor pa je imel zelo neenakomerno razporejeno vlažnost z nekoliko višjimi vrednostmi v rdeče obarvanih in z visoko vlažnostjo v rjavo obarvanih območjih v deblu.

Ugotovili smo, da je hitrost sušenja v začetni fazi največja pri redkejšem lesu divjega kostanja in najmanjša pri robiniji, kjer se je zaradi nizke začetne vlažnosti ta faza zelo hitro zaključila. Z dodatnimi merjenji permeabilnosti smo ugotovili, da je beljava zelo permeabilna, medtem ko sta bili obe obarvani področji zelo slabo permeabilni.

Slabo difuzivnost robinje potrjujejo tako nizki difuzijski koeficienti (Preglednica 4) kot tudi daljši polovični uravnovesni časi sušenja (Preglednica 5). Rezultati niso presenetljivi, saj je sposobnost lesa za prevajanje vezane vode odvisna od poroznosti oziroma gostote, saj robinijo uvrščamo v skupino gostejših lesnih vrst, ki je pogosto tudi intenzivno otiljena. Zaradi manjšega deleža beljave pri robiniji nismo mogli narediti ustreznih vzorcev in izvesti primerjave med beljavo in jedrovino. Da so izračunani difuzijski koeficienti pri debelejših sortimentih manjši, je potrjeno tudi v literaturi (Remond et al. 2005; Straže & Gorišek, 2009). Difuzijske karakteristike lesa divjega kostanja in javorja so bile podobne in v pričakovani korelaciji z gostoto.

Vlažnostni gradienti so bili pri vseh vrstah relativno nizki, zato tudi niso nastale velike sušilne napetosti in les ni razpokal. Zaradi velike nevarnosti kolapsa je nujno previdno sušenje sveže javorovine, zaradi večjega števila grč in večjih odklonov vlaken pa je pogostejše veženje. Polovično uravnovesni časi kažejo na dolgotrajnejše sušenje debelejših sortimentov robinije, zelo previdno pa je treba sušiti tudi javorovino.

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