LES/WOOD Vol. 69, No. 2, 5-20
DOI: https://doi.org/10.26614/les-wood.2020.v69n02a09

INTER-TREE VARIABILITY OF AUTUMN LEAF PHENOLOGY OF EUROPEAN BEECH (*FAGUS SYLVATICA*) ON A SITE IN LJUBLJANA, SLOVENIA

VARIABILNOST JESENSKE LISTNE FENOLOGIJE MED DREVESI NAVADNE BUKVE (*FAGUS SYLVATICA*) NA RASTIŠČU V LJUBLJANI

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UDK 630*181.8:630*176.1 *Fagus sylvatica*
Original scientific article / Izvirni znanstveni članek

Received / Prispelo: 23. 11. 2020
Accepted / Sprejeto: 2. 12. 2020

Abstract / Izvleček

Abstract: *Temporal variability of leaf senescence (autumn phenology) was observed in 2020 in 11 European beech* (Fagus sylvatica) *trees in Tivoli, Rožnik and Šišenski hrib Landscape Park in Ljubljana, Slovenia, and also observed for spring phenology in the same year. General leaf colouring, BBCH94, occurred between 19 and 24 October 2020, with lower inter-individual variability than that of leaf unfolding, BBCH11. The trees had active leaves (time between leaf unfolding and leaf colouring) between 177 and 199 days. In only three trees total leaf fall, BBCH97, occurred before 19 November 2020. Leaf colouring of the tree included in the long-term monitoring program of the Slovenian Environment Agency ARSO occurred on 24 October 2020. This is 7 days later than the 65-year average of the same tree/location and is ascribed to weather conditions. Investigation of tree tissues showed that the width of the last formed tree-ring in the wood varied between 0.39 and 9.61 mm and in the phloem between 0.09 and 0.26 mm, and that the tissues reflect the health condition of the trees.*

Keywords: *leaf phenology, autumn, leaf colouring, leaf fall, wood formation, inter-individual variability, European beech* (Fagus sylvatica)*, Slovenia*

Izvleček: *V letu 2020 smo spremljali jesensko fenologijo listov 11 dreves navadne bukve* (Fagus sylvatica) *v Krajinskem parku Tivoli, Rožnik in Šišenski hrib v Ljubljani, Slovenija. Na teh drevesih smo spomladi 2020 spremljali proces olistanja. Splošno obarvanje listov, BBCH94, je nastopilo med 19. in 24. oktobrom 2020, v ožjem časovnem intervalu kot spomladansko olistanje, BBCH11. Drevesa so imela aktivne liste (čas med olistanjem in obarvanjem listov) od 177 do 199 dni. Samo s treh dreves je do 19. novembra 2020 odpadlo vse listje, BBCH97. Pri drevesu, ki je vključeno v dolgoletni program spremljanja fenologije listov Agencije Republike Slovenije za okolje ARSO, je obarvanje listov nastopilo 24. oktobra 2020, kar je za 7 dni kasneje od 65-letnega povprečja za isto drevo / lokacijo. Raziskave drevesnih tkiv so pokazale, da je znašala širina zadnje branike v lesu med 0,39 in 9,61 mm in v floemu med 0,09 in 0,26 mm in da tkiva nakazujejo zdravstveno stanje dreves.*

Ključne besede: *fenologija, jesen, obarvanje listov, odpad listov, nastajanje lesa, variabilnost med osebki, bukev* (Fagus sylvatica)*, Slovenija*

1 INTRODUCTION
1 UVOD

The main leaf phenology events in temperate trees like European beech (*Fagus sylvatica*) are often divided into spring and autumn phenology. Spring phenology has generally been studied more frequently than autumn phenology (Gallinat et al., 2015), which covers the processes related to leaf senescence, including leaf colouring and leaf fall before the tree enters winter dormancy (Žust, 2015). Phenology is generally driven by climate (Doi & Takahashi, 2008), but there exist species-specific responses to climate (Ibáñez et al., 2010). Higher summer temperatures generally delay the occurrence of leaf senescence in beech in autumn (Čufar et al., 2012), and some models predict delayed leaf colouring for beech of 1.4 and 1.7 days per decade due to progressing climatic change (Delpierre et al., 2009). On the other hand, leaf senescence may be advanced due to summer drought, extremely high temperatures which damage the leaves, low temperatures and

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inversions (Schuster et al., 2014).

Foliar senescence which can be visually observed is accompanied by cessation of xylem and phloem formation by the cambium, which can only be studied under the microscope after tissue sampling and preparation (Čufar et al., 2008; Prislan et al., 2013a, 2013b). The combination of the two approaches is therefore of great research interest (Čufar et al., 2008; Dox et al., 2020).

Observations of leaf phenology of European beech are included in the Slovenian National Phenological Network of the Slovenian Environment Agency (ARSO) within the Ministry of Environment and Spatial Planning coordinated by the International Phenological Gardens (IPG) (The international …, 2020; Chmielewski et al., 2013; Žust, 2015). In autumn they monitor the general leaf colouring and leaf fall (Žust, 2015).

A study based on data on leaf phenology in beech collected by ARSO from 47 localities in Slovenia (altitudes 55 to 1,050 m a.s.l.) in the period 1955-2007, showed that general leaf colouring occurred between 2 October and 29 October (day of the year (DOY) 275-302). It occurred earlier at higher altitudes (1.9 days earlier per 100 m altitude increase). Leaf colouring was found to be positively correlated with temperatures from August to September, whereas long-term trends and relation to altitude were not statistically significant (Čufar et al., 2012).

In addition to the long-term observations of ARSO on representative trees, we need better knowledge on the variability of phenological events in the same species (inter-individual or between tree variability) and in the same tree (intra-individual or within tree variability). A study on deciduous trees in temperate latitudes showed that the inter-individual variability of spring phenology depends on the species, tree size and autumn phenology of the previous year (Denéchère et al., 2019). The same study proposed a minimum sample size of 23 trees to follow leaf senescence, and showed that the within-population average standard deviation was nearly two times larger for leaf senescence (8.5 days) than for budburst (4.0 days).

A recent study on the variability of spring phenology, i.e. leaf development, in European beech growing on a site in Ljubljana-Tivoli, Slovenia, showed that general leaf unfolding in different trees on the same site occurred within an interval of almost three weeks (between 7 and 25 April 2020) (Škrk et al., 2020a). Moreover, the occurrence and duration of more precisely defined phases of leaf development showed large variations within and between trees. Among the observed trees was also a standard beech tree (*Fagus sylvatica* Hardegsen, plant identification number 221, planting year 1969, origin Germany) included in the long-term monitoring program of ARSO; its leaf unfolding was observed on 14 April 2020, which was 4 days earlier than the long-term average of the same tree/location (Škrk et al., 2020a). Early leaf development in 2020 was ascribed to the above-average temperatures in winter 2019/2020.

As the beech trees in Ljubljana-Tivoli observed in spring 2020 provided valuable information on inter-tree variability on spring phenology, we continued their monitoring till late autumn of 2020. The aim of the present study is to present the progression of leaf senescence, especially leaf colouring and leaf fall, and to relate them to climate data and long-term leaf colouring data for beech in Ljubljana. In addition, we evaluated the condition of tree tissues, last formed wood and phloem, sampled around the day of general leaf colouring and their possible use to evaluate the growth potential and health condition of the trees.

2 MATERIALS AND METHODS
2 MATERIAL IN METODE

2.1 STUDY SITE AND TREES
2.1 OPAZOVANA PLOSKEV IN DREVESA

The selected study area was Tivoli, Rožnik and Šišenski hrib Landscape Park in Ljubljana. The 11 trees selected for observation were observed daily for leaf phenology in spring of 2020 (Škrk et al., 2020a, 2020b). We observed the trees on three locations: (1) trees 11-19 and (2) tree 20 – all on the pathway Pod Turnom, near the water reservoir; and (3) tree 30 near the Cekin Mansion, which is included in the long-term monitoring of the Slovenian National Phenological Network (*Fagus sylvatica* Hardegsen, plant identification number 221, planting year 1969, origin Germany) of the Slovenian Environment Agency as a part of the International Phenological Gardens of Europe (Figure 1).

*Figure 1. Study trees on 10 September 2020 before the onset of autumn leaf colouring. Trees 11-20 belong to a beech forest site, while tree 30 grows in the park and is a clone (*Fagus sylvatica* Hardegsen) included in the International Phenological Gardens for long-term observations of leaf phenology conducted by ARSO.*
*Slika 1. Preučevana drevesa 10. septembra 2020 pred nastopom jesenskega obarvanja listov. Drevesa 11–20 pripadajo območju bukovega gozda, medtem ko drevo 30 raste v parku in je klon (*Fagus sylvatica* Hardegsen), vključen v Mednarodni fenološki vrt za dolgoročno opazovanje fenologije listov, ki ga opravlja ARSO.*

The geographical coordinates of trees and tree group are between 46.052697°- 46.058247° N, 14.489115° and 14.495366° E, and 307-316 m a.s.l. (Škrk et al., 2020a).

2.2 FIELD OBSERVATIONS OF LEAF PHENOLOGY
2.2 TERENSKA OPAZOVANJA RAZVOJA LISTOV

For monitoring phenological phases of leaf colouring we visited the selected trees between 10 September and the end of November 2020. First, we observed them once a week, but then with the onset of leaf colouring and its intense progress we observed them 3 times a week. We took digital photos of all selected trees. We recorded general leaf colouring (yellowing) (BBCH94), which occurs when more than half of the leaves turn yellow in autumn (Table 1) (Žust, 2015). In addition, we also took notes on leaf fall, BBCH97, when 100% of leaves fell down from trees to the ground (Koch et al., 2009; Žust, 2015) if it occurred till 19 November 2020.

For a better overview of leaf colouring and leaf fall we also took panoramic photos of the observed site. The photos were taken from the Nebotičnik skyscraper and from the Ljubljana Castle hill.

2.3 CLIMATIC AND PHENOLOGICAL DATA FOR COMPARISON
2.3 KLIMATSKI IN FENOLOŠKI PODATKI ZA PRIMERJAVO

To illustrate the weather conditions during the observed leaf colouring we used the daily meteorological data, minimum and maximum temperatures and sums of precipitation for Ljubljana for the period May-Nov 2020 and compared them to the long-term average for

Table 1. Description of autumn phenological phases
Preglednica 1. Opis jesenskih faz listne fenologije

Phase / Faza	Name / Ime	Description	Opis faze
BBCH94	General leaf colouring (yellowing) / Splošno obarvanje (rumenenje) listov	More than 50% of the leaves turn yellow	Več kot polovica listov jesensko obarvanih
BBCH97	General leaf fall / Splošno odpadanje listov	100% of leaves fell down from trees to the ground	100 % listov odpade z dreves

1981-2010. Climatic data were obtained from the online meteorological archive ARSO METEO (ARSO, 2020).

The observed leaf colouring was compared with long-term phenological data of general leaf colouring for Ljubljana for the period 1955-2019 from the database of the Slovenian National Phenological Network of ARSO (Žust, 2015).

2.4 MICROCORE SAMPLING AND INCREMENT OF WOOD AND PHLOEM

2.4 ODVZEM MIKRO IZVRTKOV IN PRIRASTEK LESA IN FLOEMA

As tree size and vitality might affect leaf phenology, we also measured the diameters at breast height (1.3 m) for 7 characteristic trees (numbers 11, 12, 13, 14, 19, 20, 30). As trees grow in an important recreation area representing the "green lungs" of Ljubljana, they cannot be cored to determine their ages. Therefore, we estimated the age based on nearby felled trees. To estimate the current growth with minimal tree wounding, we took microcores from the 6 selected trees. The microcores were taken from the stems on 13 October 2020 with a Trephor tool at 1.3 m above ground. The microcores were processed in agreement with the methodology of sample collection and tissue preparation protocol of Prislan et al. (2013a, 2014). The 9 µm thick transverse sections stained with safranin and astra blue were observed with a Nikon eclipse 800 light microscope, and analysed with NIS Elements image analysis program.

We inspected the condition (state of differentiation, cell characteristics) and measured the dimensions (width and cell number) of the tissues including cambium, last formed xylem and phloem increments of 2020 along the three radial files (Prislan et al., 2013a).

Figure 2. Variability of leaf colouring (a) among trees and within the same tree, and (b) within the same branch on 31 October 2020 (DOY 305).

Slika 2. Razlike v obarvanju listov (a) med drevesi in znotraj istega drevesa ter (b) znotraj iste veje 31. oktobra 2020 (dan 305).

3 RESULTS AND DISCUSSION
3 REZULTATI IN RAZPRAVA

3.1 DYNAMICS OF AUTUMN LEAF COLOURING IN 2020
3.1 DINAMIKA JESENSKEGA OBARVANJA LISTOV V LETU 2020

On 10 September 2020 the observed trees had some yellow leaves, but the majority were green (Figure 1). After that date we recorded the gradual onset of leaf colouring, which varied within the same tree and between the trees (Figure 2). Leaf colouring often first occurred near the top of a tree and progressed towards the lower parts of the crown. While the top was already yellow or the leaves already started to fall, the leaves at the bottom of the tree could still be green. There were also great differences in progress of leaf colouring within the same branches.

Leaf colouring was slowly progressing from the end of September till mid-October, and became faster especially after 20 October, when most trees changed leaf colour within a few days (Figures 3, 4, 5).

General leaf colouring, when more than 50% of leaves turned yellow, as defined by IPG (Table 1), was first observed in trees 12 and 14 (DOY 293), two days later in tree 11 (DOY 295), followed by tree 19 (DOY 296). In trees 20 and 13 general leaf colouring was observed on 23 October (DOY 297) (Figures 4, 5, 6, Table 2). The photos also show the dynamics of leaf fall. Interestingly, tree 14, which had the latest leaf unfolding in spring, was the first tree which lost all its leaves by the end of October. By 19 November, trees 11 and 12 also lost all their leaves. Tree 19 did not vary from other trees regarding timing of leaf colouring, while in spring this tree had a very late leaf unfolding (Figure 6, Table 2). Tree 19 grows solitary after the nearby trees were damaged by an ice storm in February 2014, and has been reported to show a decline characterized by death of shoots, twigs, branches and translucent and sparse canopy (Ogris, 2020).

Compared to the spring dynamics of leaf unfolding, when the difference between the earliest and latest tree was 18 days, the timing of general leaf colouring was less variable; with a difference between the earliest and the latest leaf colouring of 5 days (Table 2).

Leaf fall phase (BBCH97), when 100% of leaves fall from trees to the ground, mainly depends on

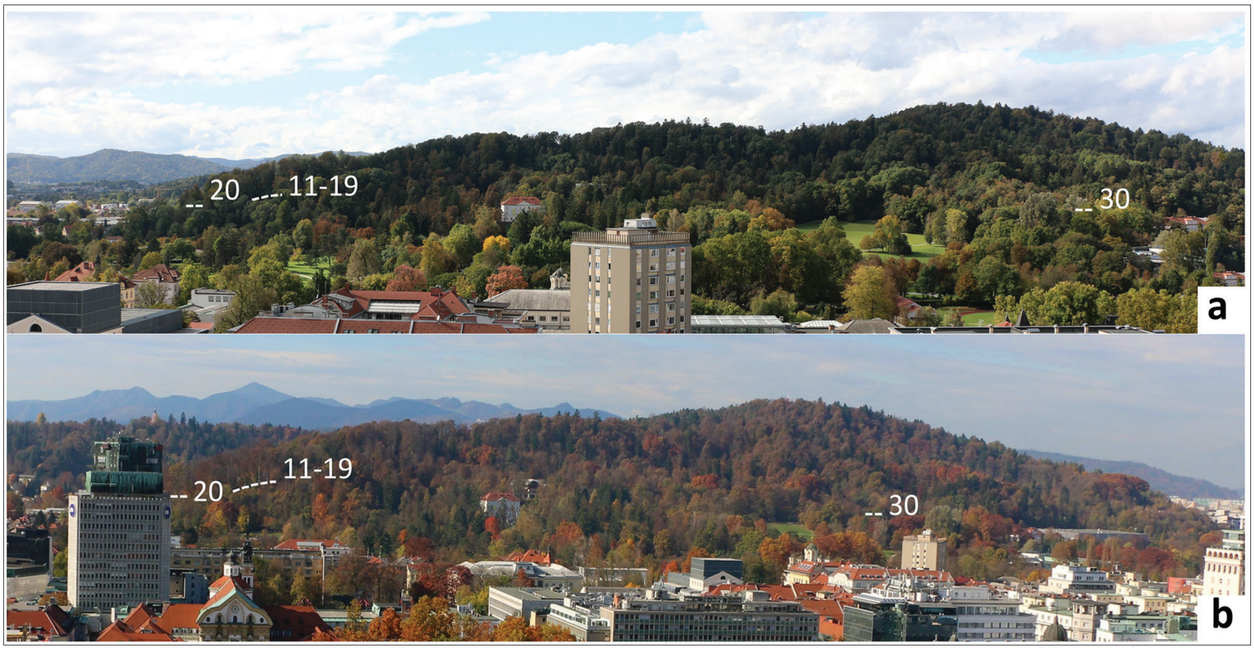

Figure 3. Study site and trees in Tivoli, Rožnik forest as seen (a) from the Ljubljana Skyscraper (Nebotičnik) on 24 September (DOY 268) and (b) from the Ljubljana Castle on 30 October 2020 (DOY 304).

Slika 3. Opazovano območje in drevesa na območju krajinskega parka Tivoli, Rožnik, fotografirana (a) z ljubljanskega Nebotičnika 24. septembra (dan 268) in (b) z Ljubljanskega gradu 30. oktobra 2020 (dan 304).

Figure 4. Phenology of leaf senescence in the observed beech trees between 18 September (DOY 262) and 25 October 2020 (DOY 299).

Slika 4. Fenologija senescence listov opazovanih bukev med 18. septembrom (dan 262) in 25. oktobrom 2020 (dan 299).

Figure 5. Phenology of leaf senescence in the observed beech trees between 28 October 2020 (DOY 302) and 22 November 2020 (DOY 327).
Slika 5. Fenologija senescence listov opazovanih bukev med 28. oktobrom (dan 302) in 22. novembrom 2020 (dan 327).

current conditions (wind, rain etc). Gradual leaf fall started soon after leaf colouring, with the exception of tree 30. Total leaf fall was by 19 November 2020 only observed in 3 trees, while on the other trees the leaves wilted after 21 November when the temperature fell below zero for the first time. After that time, and especially on trees 20 and 30, some of the leaves remained attached to the twigs.

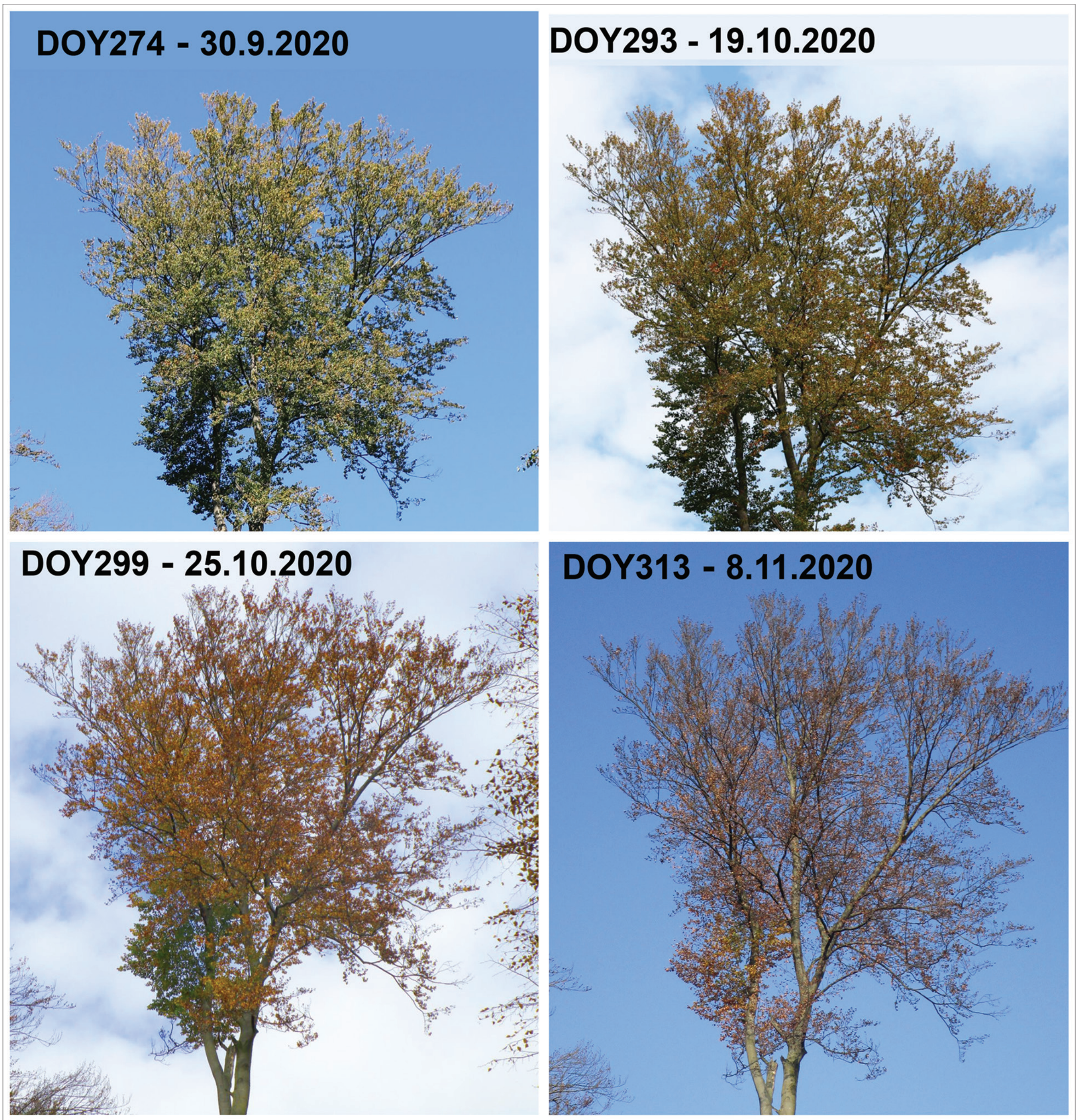

Figure 6. Tree 19 – detailed views of the crown with progressing leaf senescence from September till November 2020.

Slika 6. Drevo 19 - podroben pogled na krošnjo in napredovanje senescence listov od septembra do novembra 2020.

Table 2. Dates of general leaf colouring compared to dates of leaf unfolding, days with active leaves (days between leaf unfolding and leaf colouring) and a note if the leaf fall occurred by 19 November 2020.
Preglednica 2. Datumi splošnega obarvanja listov pri izbranih drevesih, datumi razvoja listov, dnevi z aktivnimi listi (dnevi med olistanjem in obarvanjem listov) in zaznamek, če je bil odpad listov zaključen do 19. novembra 2020.

Tree / Drevo	Leaf unfolding / Razvoj listov		Leaf colouring / Obarvanje listov		Days with active leaves / Dnevi z aktivnimi listi	Leaf fall till 19 Nov 2020 / Odpad listov do 19.11.2020
	Date / Datum	DOY / Dan v letu	Date / Datum	DOY / Dan v letu	Days / Dnevi	
11	9.4.2020	100	21.10.2020	295	195	yes / da
12	9.4.2020	100	19.10.2020	293	193	yes / da
13	16.4.2020	107	23.10.2020	297	190	
14	25.4.2020	116	19.10.2020	293	177	yes / da
19	22.4.2020	113	22.10.2020	296	183	
20	7.4.2020	98	23.10.2020	297	199	
30	14.4.2020	105	24.10.2020	298	193	
Average / Povpr.		106		296	190	
Minimum / Min.		98		293	177	
Maximum / Maks.		116		298	199	
STD		6.90		1.99	7.55	

3.2 LEAF COLOURING IN THE LIGHT OF LONG-TERM OBSERVATIONS
3.2 OBARVANJE LISTOV V LUČI DOLGOLETNIH OPAZOVANJ

In tree 30 (included in the long-term phenology monitoring of ARSO) general leaf colouring occurred at the latest date, on 24 October, DOY 298 (Figure 7, Table 2). On 22 November (DOY 327) the tree still had numerous brown wilted leaves in the upper part of the crown (Figure 5). This agrees with the observation of numerous wilted leaves in the upper crown observed in spring of 2020. The wilted leaves of the previous year remained on the tree till the unfolding of new leaves in spring (Škrk et al., 2020a, 2020b).

As mentioned before, tree 30 is a reference tree for Ljubljana monitored in the framework of the Slovenian National Phenological Network included in the IPG (plant number 221), and is one of a series of genetically identical trees that are planted all over Europe (The international ..., 2020).

Leaf colouring in Ljubljana has varied over time. The long-term (1955-2019) average day of leaf colouring is 18 October (DOY 291, when not a leap year as in 2020). The earliest leaf colouring in this tree was observed on DOY 270 (27 September 1979), and the latest on DOY 307 (3 November 1991 and 1997) (Figure 8). In 2020 leaf colouring of tree 30 was observed on DOY 298 (24 October 2020), which is 7 days later than the long-term average.

In Ljubljana there is a general trend towards later leaf colouring, but Čufar et al. (2012) showed that the trend was not statistically significant in the period 1955-2007.

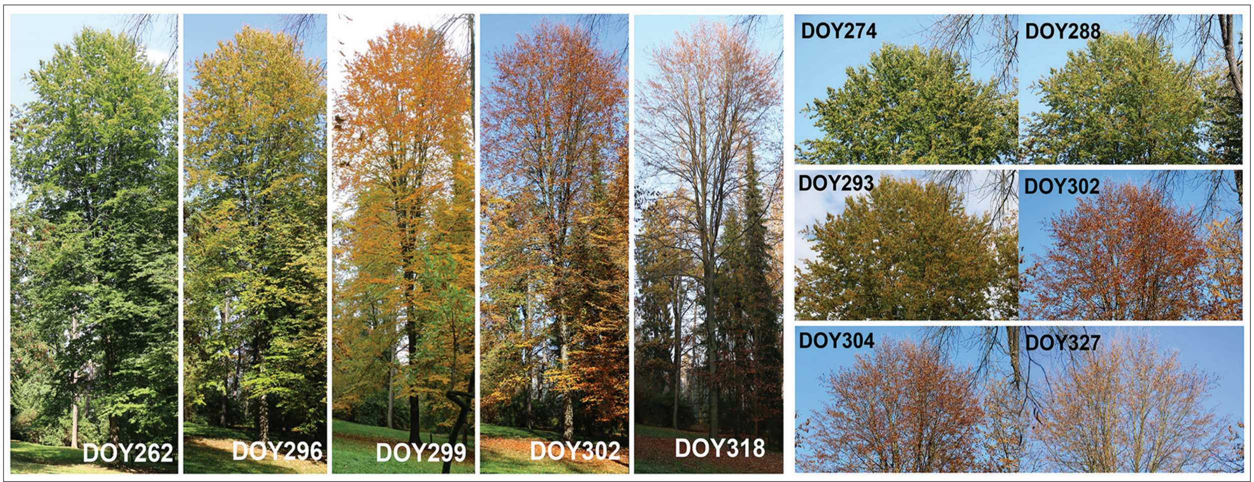

*Figure 7. Progression of leaf colouring in tree 30 between 18 September (DOY 262) and 22 November (DOY 327) with detailed view of crown top. General leaf colouring occurred on 24 October 2020 (DOY 298). The tree (*Fagus sylvatica* Hardegsen, plant identification number 221, planting year 1969, origin Germany) is included in the long-term monitoring of the Slovenian National Phenological Network of the Slovenian Environment Agency (ARSO).*

*Slika 7. Napredovanje obarvanja listov na drevesu 30 med 18. septembrom (dan 262) in 13. novembrom (dan 318) s podrobnim pogledom vrha krošnje. Splošno obarvanje listov se je zgodilo 24. oktobra 2020 (dan 298). Drevo (*Fagus sylvatica* Hardegsen, identifikacijska številka rastline 221, leto sajenja 1969, poreklo Nemčija) je vključeno v dolgoročno spremljanje fenologije v okviru Slovenske nacionalne fenološke mreže Agencije RS za okolje (ARSO).*

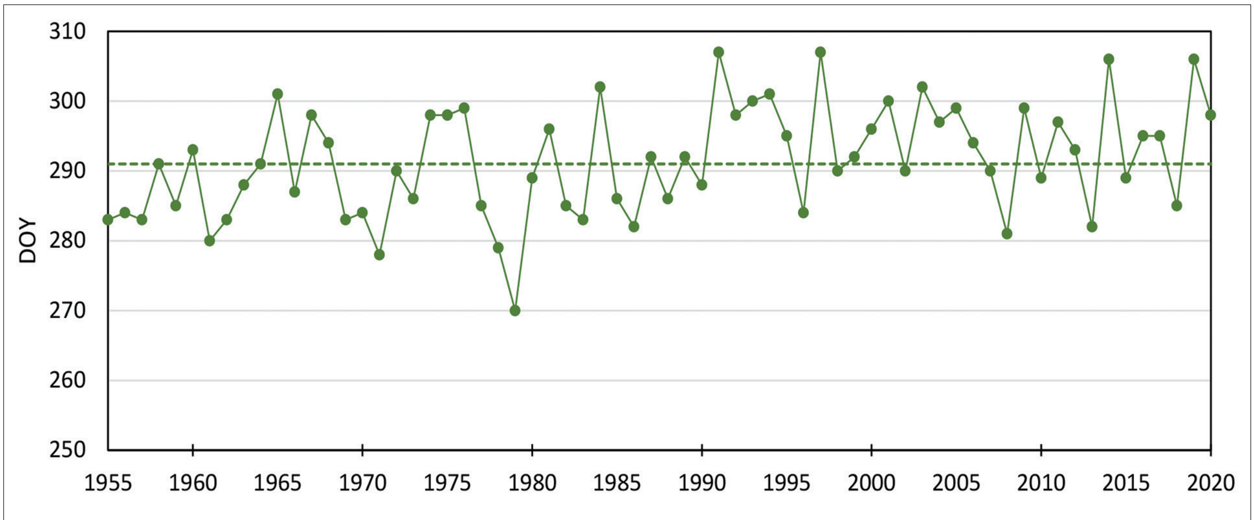

Figure 8. General leaf colouring of beech 30 in Ljubljana (plant 221, IPG) in the period 1955-2020 and the corresponding average (dotted line). DOY - day of the year. Data ARSO (2020).

Slika 8. Dan obarvanja listov bukve 30 v Ljubljani (drevo 221, IPG) v obdobju 1955-2020 in pripadajoče povprečje (črtkana črta). DOY – zaporedni dan v letu. Podatki ARSO (2020).

3.3 WEATHER CONDITIONS AND THEIR IMPACT ON LEAF SENESCENCE
3.3 VREMENSKE RAZMERE IN NJIHOV VPLIV NA SENESCENCO LISTOV

Summer 2020 in Slovenia was warmer (+0.9°C) and wetter (119% precipitation) than the long-term average 1981-2010. The surplus in temperature was relatively small in June and July, whereas August was significantly warmer than the long-term average. Nevertheless, summer 2020 generally had a lower temperature than other summers in the last 5 years. In Ljubljana the maximum summer temperature in 2020 was 33.2°C, with 25 days with a maximum daily temperature of at least 30°C (Figure 9). The sum of precipitation exceeded the long-term average on most summer days in Ljubljana (Cegnar, 2020).

September 2020 was also warmer (+1.5°C) than the long-term average in Ljubljana, but had only 90% of the long-term precipitation. The last 5 days of September were cooler. The average temperature in October was 11.9°C, which is 0.6°C warmer than usual. The amount of precipitation was 138% compared to the long-term average. There was a slight cool-wet period after 10 October 2020.

According to the weather conditions in summer and autumn 2020, it was less likely that summer temperatures would damage the leaves and cause premature leaf colouring. Therefore, warm and moderately wet conditions in summer and autumn 2020 most likely favoured later occurrence of leaf colouring and leaf fall.

3.4 CAMBIUM, WOOD AND PHLOEM AT THE TIME OF LEAF COLOURING
3.4 KAMBIJ, LES IN FLOEM V ČASU OBARVANJA LISTOV

Investigation of tree tissues collected from the trees by micro-coring in mid-October (around the long-term average day of leaf colouring) showed that wood formation was completed in all trees, except in one (tree 30). The width of the last formed tree ring 2020 in the wood varied between 0.39 and 9.61 mm and in the phloem between 0.09 and 0.26 mm (Table 3). The trees in general had very narrow late phloem with mainly 1-2 cells per radial row.

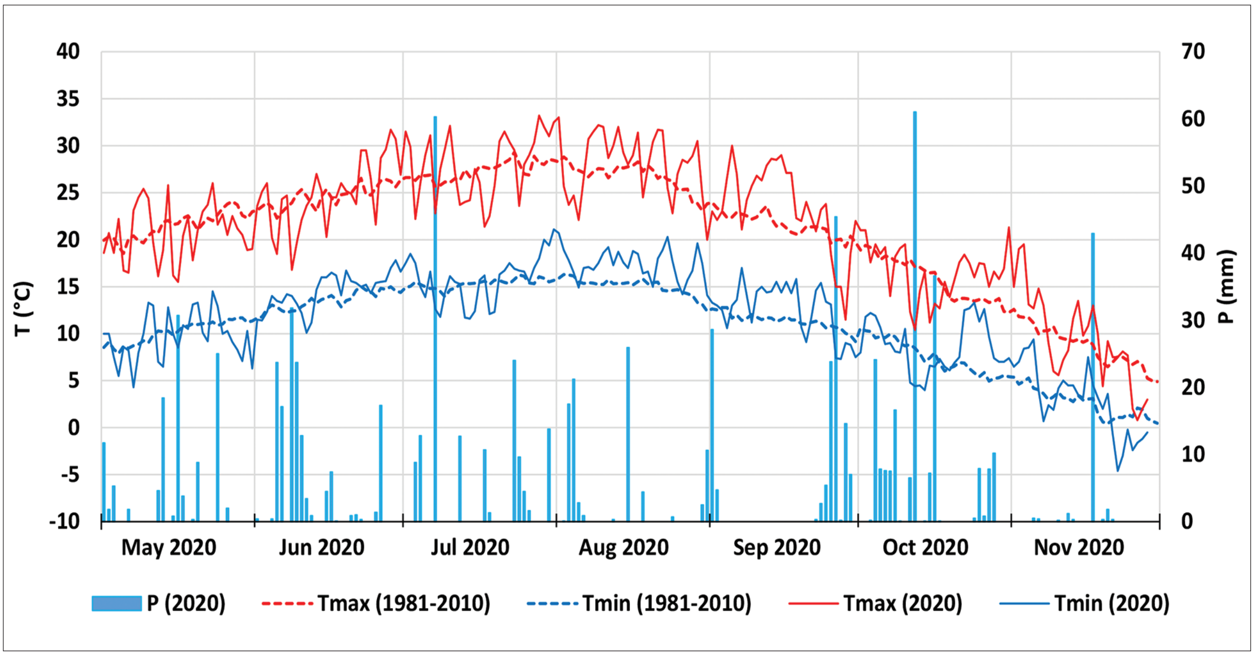

Figure 9. Minimum and maximum daily temperatures (T) and precipitation (P) in Ljubljana between May and November 2020 and average minimum and maximum temperatures for the period 1981-2010 (data ARSO, 2020).

Slika 9. Minimalne in maksimalne dnevne temperature (T) ter padavine (P) v Ljubljani od maja do novembra 2020 in povprečne minimalne ter maksimalne temperature za obdobje 1981-2010 (podatki ARSO, 2020).

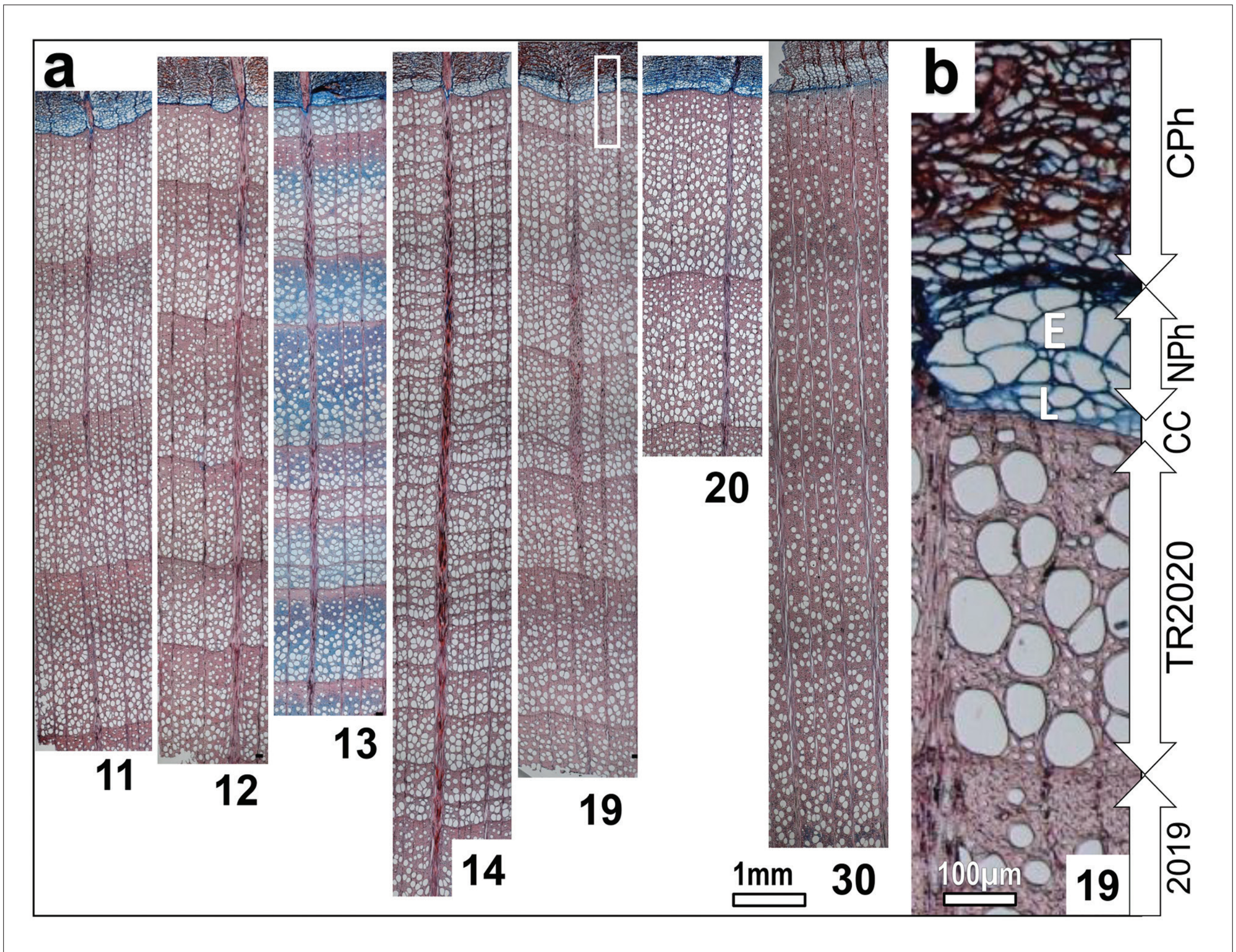

Figure 10. Cross-sections of microcores showing: (a) wood, cambium and bark, and (b) detailed view of the tree 19 with last formed xylem tree-ring 2020 (TR2020), cambium (CC), non-collapsed phloem (NPh), divided in early (E) and late phloem (L), and part of the bark with collapsed phloem (CPh).
Slika 10. Prečni prerezi mikro-izvrtkov, ki prikazujejo: (a) les, kambij in del skorje in (b) podroben pregled tkiv drevesa 19 vključno z zadnjo ksilemsko braniko 2020 (TR2020), kambijem (CC), nekolabiranim floemom (NPh), razdeljenim na rani (E) in kasni floem (L) ter delom kolabiranega floema (CPh).

The observed trees are characterized by large diameters and heights (Table 3). The characteristics of trees 11-20 growing on the location of natural beech forest deviate from those of tree 30, which is a clone growing in the phenological garden.

Trees 11-20 have an estimated age ca. 120-150 years based on tree-ring count of the nearby felled trees. Their cross-sections showed that the cambium already stopped the production of wood and phloem, and that the wood differentiating was completed (with the exception of tree 30). The width of the last formed xylem tree-ring 2020 (TR2020) varied between 0.39 and 2.34. Tree 14 had the narrowest tree-rings especially after 1993 (average 0.38 mm for 1994-2020). Tree 14 was also the latest in spring phenology, the first in leaf colouring and the first which lost all leaves, in line with the findings of Fu et al. (2014). Two trees (13 and 19) showed a pronounced reduction of tree-ring width in 2020, which might be related to tree decline reported for beech in Tivoli (Ogris, 2020).

Trees 11-20 have growth rings 2020 in the phloem between 90 and 185 µm wide, with 3-5 early phloem (E) and 1-2 late phloem (L) cells. LP is generally narrower than in trees at Panška reka with similar climatic conditions (Prislan et al., 2013a).

The characteristics of tree 30 deviated from the ones of the other trees (Table 3). This is possibly

Table 3. European beech (Fagus sylvatica)*, Ljubljana: tree diameter at breast height (DBH), 2020 xylem and phloem ring width, and number of cells in early and late phloem on DOY 287 (13 October, 2020).*
Preglednica 3. Navadna bukev (Fagus sylvatica)*, Ljubljana: premeri dreves na prsni višini (DBH), širine ksilemske in floemske branike, nastale v letu 2020, ter število celic v ranem in kasnem floemu na dan 287 (13. oktober 2020).*

Tree / Drevo	DBH / Premer	Xylem ring width 2020 / Širina ksilemske branike 2020	Phloem ring width 2020 / Širina floemske branike 2020	Early phloem / Rani floem	Late phloem / Kasni floem
	[cm]	[mm]	[µm]	Number of cells / Število celic	
11	68	1.73	175	5	2
12	64	1.07	169	4	1
13	59	0.39	90	3	1
14	66	0.48	185	6	1
19	58	0.40	182	4	1
20	70	2.34	147	5	2
30	53	9.61	256	3	4
Average / Povpr.	62	2.29	172	4	2
Minimum / Min.	53	0.39	90	3	1
Maximum / Maks.	70	9.61	256	6	4
STD	6.27	3.31	49.48	1.11	1.11

because tree 30 is a clone, grows in the park (ca. 600 m apart from the other observed beech trees), had the smallest diameter, height and possibly age (ca. 50-60 years), the largest xylem (9.61 mm) and phloem ring (256 µm) formed in 2020, and the widest late phloem (4 cells). It was the only tree where differentiation of the last formed xylem was not yet completed (Figure 10). The tree also had the latest leaf colouring (Figures 1, 3, 7, 8, Tables 2, 3) and leaves which were wilted at the end of November, but may remain on the tree till the next leaf unfolding (as observed in spring of 2020).

4 CONCLUSIONS
4 ZAKLJUČKI

We present inter-tree variability in the autumn leaf phenology of selected beech trees in Ljubljana, which were also monitored in spring of the same year, 2020 (Škrk et al., 2020a). Although there were large differences in the dynamics of spring phenology with an 18-day difference for leaf unfolding phase, all selected trees reached leaf colouring, phase BBCH94, within a 5-day interval between 19 and 24 October 2020. Although changes were gradual from mid-September, they became very rapid after 19 October, when a large percentage of tree leaves changed colour within a few days. We also observed a high intra-individual variability. Trees 12 and 14, which grow in the immediate vicinity, were the first to have 50% of all leaves coloured (DOY 293). The last leaf colouring was observed in tree 30, which is a clone and is included in the International Phenological Gardens. In tree 30, leaf colouring occurred 7 days later compared to the long term average (DOY 298).

Leaf senescence is mostly affected by summer temperatures and by maximum temperatures from September to October. According to ARSO, temperatures in Ljubljana are generally increasing, which results in a general delay in leaf senescence in autumn. On the observed site the summer was very warm with an above average amount of precipitation. October 2020 in particular was warmer than long term average, and it also had 38% more precipitation, which might favour a delay in leaf colouring.

Since temperatures may be a dominant factor, we can expect, in the context of global warming, delayed dates of leaf senescence in areas without water limitation, such as Ljubljana.

5 SUMMARY

5 POVZETEK

Jesenska fenologija listopadnih dreves, kot je navadna bukev (*Fagus sylvatica*), proučuje obarvanje in odpadanje listov, preden drevo vstopi v zimsko mirovanje (Žust, 2015) in tudi fenološke dogodke, povezane s prenehanjem kambijeve produkcije lesa in floema (Čufar et al., 2008; Prislan et al., 2013a, 2013b).

Opazovanje listne fenologije navadne bukve je vključeno v Slovensko nacionalno fenološko mrežo Agencije RS za okolje (ARSO) pri Ministrstvu za okolje in prostor (Žust, 2015).

Predhodna študija fenologije listov bukve je na osnovi podatkov, ki jih je zbral ARSO na 47 rastiščih po Sloveniji (nadmorske višine od 55 do 1.050 m) v obdobju 1955-2007, pokazala, da obarvanje več kot polovice listov pri bukvi v Sloveniji nastopi od 2. do 29. oktobra. Obarvanje se pojavi prej na višjih nadmorskih višinah in je pozitivno povezano s temperaturami od avgusta do septembra (Čufar et al., 2012).

V Krajinskem parku Tivoli, Rožnik in Šišenski hrib v Ljubljani smo spomladi 2020 opazovali 11 izbranih bukev in pridobili informacije o razlikah spomladanskega razvoja listov med drevesi. Namen tokratne študije pa je bil spremljati proces senescence listov, zlasti obarvanja in odpada listov ter jih povezati z vremenskimi in dolgoročnimi fenološkimi podatki. Poleg tega smo ocenili stanje drevesnih tkiv, kambija, lesa in floema sredi oktobra.

Za spremljanje obarvanja listov smo izbrana drevesa opazovali od 10. septembra do konca novembra 2020. Ob vsakem opazovanju smo jih fotografirali in pripravili galerije slik (slika 1, 4, 5, 6, 7). Zabeležili smo splošno obarvanje (rumenenje) listov (BBCH94), ko se obarva več kot polovica listov (preglednica 1), in odpad listov, ki se zaključi s fazo BBCH97, ko je 100 % listov odpadlo z drevesa (Žust, 2015). Za boljši pregled obarvanja in odpada listov smo posneli tudi panoramske fotografije opazovanega rastišča. Fotografije smo posneli z ljubljanskega Nebotičnika in z Ljubljanskega gradu (slika 3).

Za proučevanje vremenskih razmer smo uporabili dnevne podatke za Ljubljano iz spletnega meteorološkega arhiva ARSO METEO. Obarvanje listov smo primerjali z dolgoročnimi fenološkimi podatki za Ljubljano za obdobje 1955-2019 iz baze podatkov Slovenske nacionalne fenološke mreže ARSO (Žust, 2015). Opravili smo tudi odvzem mikro izvrtkov pri 7 drevesih, izmerili premere dreves in ocenili njihovo starost. Mikro izvrtke iz debel dreves smo odvzeli 13. oktobra 2020 z orodjem Trephor, jih obdelali in pripravili v skladu s protokolom, ki ga je predlagal Prislan s sodelavci (2013a, 2014) ter pripravili prečne prereze za opazovanje pod mikroskopom.

Splošno obarvanje listov, BBCH94, je nastopilo med 19. in 24. oktobrom 2020, v ožjem časovnem intervalu kot spomladansko olistanje, BBCH11. Drevesa so imela aktivne liste (dnevi med olistanjem in splošnim obarvanjem listov) od 177 do 199 dni. Samo s 3 dreves je do 19. novembra odpadlo vse listje (slike 2, 4, 5, 6, 7, 8, preglednica 2). Pri ostalih drevesih je po prvi zmrzali 21. novembra 2020 vse listje uvelo, a je predvsem pri drevesih 20 in 30 ostalo na drevesih.

Pri drevesu 30, ki je vključeno v dolgoletni program spremljanja fenologije listov Agencije Republike Slovenije za okolje ARSO, je obarvanje listov nastopilo 24. oktobra 2020, kar je za 7 dni kasneje od 65-letnega povprečja za isto drevo / lokacijo (slika 7, preglednica 2). Na drevesu je bilo 22. novembra (DOY 327) v zgornjem delu krošnje še vedno veliko uvelih listov.

Poletje 2020 v Sloveniji je bilo toplejše (+ 0,9 °C) in bolj vlažno (119 % padavin) kot dolgoletno povprečje 1981-2010, a manj vroče kot poletja v zadnjih 5 letih. Količina padavin v Ljubljani je bila poleti za manj kot odstotek manjša od dolgoletnega povprečja. Tudi september je bil toplejši (+1,5 °C) od dolgoletnega povprečja, vendar je imel le 90 % dolgoletnih padavin. Povprečna oktobrska temperatura je bila 11,9 °C, kar je za 0,6 °C več kot običajno. Količina padavin je bila v primerjavi z dolgoročnim obdobjem večja (138 %). Opisane vremenske razmere so najverjetneje vplivale na poznejše obarvanje in odpad listov.

Drevesa 11-20, ki rastejo ob vznožju hriba na območju nekdaj naravnega bukovega gozda, so stara približno 120-150 let. Mikroskopska analiza tkiv je pokazala, da je bila kambijeva proizvodnja ter s tem diferenciacija lesa in floema sredi oktobra že zaključena (z izjemo drevesa 30). Širina zadnje branike v lesu, nastale v letu 2020, je bila pri drevesih od 0,39 do 2,34 mm. Drevo 14 je imelo najožje branike in se je spomladi olistalo zadnje, jeseni pa se je prvo obarvalo in odvrglo liste. Drevesi 13 in 19 sta imeli v letu 2020 manjši prirastek kot v predhodnih letih, kar je morda povezano s hiranjem bukve, ki so ga opazili tudi na območju Tivolija (Ogris, 2020).

Drevesa 11-20 so imela branike floema, nastale v letu 2020, široke od 90 do 185 µm, v ranem lesu smo zabeležili 3-5 celic, v kasnem pa 1-2 celici v radialnih nizih.

Drevo 30 se je v vseh pogledih razlikovalo od ostalih opazovanih dreves (preglednica 3). To je morda zato, ker je drevo klon, ki raste v parkovnem delu Tivolija. Ima najmanjši premer, višino in starost (približno 50–60 let), najširšo zadnjo ksilemsko (9,61 mm) in floemsko (256 µm) braniko, ter najširši kasni floem (4 celice), diferenciacija lesa zadnje branike pa sredi oktobra še ni bila zaključena (slika 10). Obarvanje listov je pri tem drevesu nastopilo najkasneje. S predstavljeno študijo smo orisali razlike v jesenski fenologiji med drevesi.

SUPPLEMENT
DODATEK

The supplement related to this article is available online in the Repository of the University of Ljubljana (RUL) and can be accessed through https://repozitorij.uni-lj.si/IzpisGradiva.php?id=122429, and cited as Škrk et al. (2020c).

It contains detailed photos of leaf senescence in European beech (*Fagus sylvatica*) (tree 30 in this study) which is as a plant number 221 included in the long-term monitoring of the Slovenian National Phenological Network of the Environmental Agency of the Republic of Slovenia (ARSO) within the Ministry of the Environment and Spatial Planning as a part of the International Phenological Gardens of Europe.

Dodatek, povezan s tem člankom, je prosto dostopen na spletu v Repozitoriju Univerze v Ljubljani (RUL). Dostop do njega je možen preko povezave https://repozitorij.uni-lj.si/IzpisGradiva.php?id=122429 in se ga citira kot Škrk et al. (2020c). Dodatek vsebuje podrobne fotografije senescence listov pri navadni bukvi *Fagus sylvatica* (drevo številka 30 v tej študiji), ki je kot drevo z identifikacijsko številko 221 vključeno v dolgoletno spremljanje v okviru Slovenske nacionalne fenološke mreže Agencije Republike Slovenije za okolje (ARSO) Ministrstva za okolje in prostor Republike Slovenije, ki je vključen v aktivnosti Mednarodnih fenoloških vrtov Evrope.

ACKNOWLEDGEMENTS
ZAHVALA

The study was supported by the Slovenian Research Agency (programs P4-0015 and P4-0085 and young researchers' program). Climatic and long-term phenological data were provided by the Slovenian Environment Agency (ARSO) within the Ministry of the Environment and Spatial Planning. We thank Ana Žust for her support with phenological data, as well as Paul Steed and Darja Vranjek for English and Slovene language editing, respectively.

Študijo je podprla Javna agencija za raziskovalno dejavnost republike Slovenije ARRS (programa P4-0015 in P4-0085 ter program mladih raziskovalcev). Meteorološke in dolgoletne fenološke podatke je posredovala Agencija RS za okolje (ARSO) pri Ministrstvu za okolje in prostor. Zahvaljujemo se Ani Žust za vso pomoč ter Paulu Steedu in Darji Vranjek za lektoriranje angleškega in slovenskega besedila.

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