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CARBON DIOXIDE (CO_2) EMISSIONS FROM SOILS DURING THE REGENERATION OF PEDUNCULATE OAK (*Quercus robur* L.) STAND IN THE SUMMER PERIOD

EMISIJE UGLJIKOVOG DIOKSIDA (CO2) IZ TLA TIJEKOM OBNOVE SASTOJINE HRASTA LUŽNJAKA (*Quercus robur* L.) U LJETNOM RAZDOBLJU

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SUMMARY

The loss of soil organic carbon stock and increased CO_2 emission from soil are induced by various human activities. The aim of this study was to examine whether an anthropogenic influence during the regeneration of a pedunculate oak (*Quercus robur* L.) stand can affect the increment of CO_2 emission from the soil. The research was carried out within three plots, out of which two were exposed to different degrees of anthropogenic influence. The air samples were collected using the soil respiratory chambers and analysed using the gas chromatograph Agilent 8890. Based on the obtained results, soil temperature and moisture as the most dominant drivers of the CO_2 emission had different effects on the CO_2 flux from soil depending on the intensity of anthropogenic influences and environmental conditions. Within the experimental plot with the significant soil alteration, a reliable positive correlation was detected for the CO_2 flux with the soil temperature ($r = 0.77$, $p < 0.05$). High significant correlation was observed considering soil moisture ($r = 0.85$, $p < 0.05$) in the natural soil where the application of pesticides was conducted. The results showed that both soils that were exposed to the anthropogenic influences had notably higher values of the CO_2 flux in comparison to the reference natural soil without anthropogenic impacts.

KEY WORDS: CO_2, pedunculate oak, anthropogenic influence, soil temperature, soil moisture

INTRODUCTION
UVOD

Forest ecosystems play a crucial role in global carbon cycle and are highly important factor in decreasing the negative effects of the ongoing climate change (Kuznetsova et al., 2019). Net ecosystem production is defined as the difference between the amount of organic carbon that is fixed by process of photosynthesis and total ecosystem respiration (Lovett et al., 2006). Soils are the biggest carbon pools in terrestrial ecosystems (Amundson, 2001), where amount of soil organic carbon is estimated at 3 000 Pg (Köchy et al., 2015). Soil respiration reaches 55-85% of the total ecosystem respiration in various forests (Knohl et al., 2008). The total flux of carbon dioxide (CO_2) from the soil is one of the largest emissions in the global carbon cycle (Wang et al., 2011), which releases 66-100 Pg C year^{-1} (Chiang et al., 2021). Soil respiration is divided on autotrophic respiration caused by

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root respiration and heterotrophic respiration where microorganisms have the greatest role. The contribution of the soil macrofauna to total CO_2 emission from soils is almost insignificant (Teramoto et al., 2019; Kuzyakov, 2005).

Key drivers of greenhouse gases (GHG) emissions from soils are soil temperature, humidity (soil water content), nutrients (C/N-ratios), soil pH value, land use, land cover, type and age of vegetation, local and regional climate, and hydrology (Oertel et al., 2016). Soil temperature and soil water content are the most dominant factors that affect GHG emissions from the soils (Fang and Moncrieff, 2001; Tang et al., 2003; Dilustro et al., 2005; Tang et al., 2006; Teramoto et al., 2017; Prasad and Baishya, 2019; Yu et al., 2021; Mühlbachova et al., 2022). Higher soil temperature leads to higher CO_2 emissions and higher soil respiration, which is a consequence of increased microbial activity (Oertel et al., 2016). Soil organic carbon accumulation largely depends on the vegetation cover, where land-use changes affect soil organic carbon stocks and can lead to sequestration or emission of CO_2 (Poeplau and Don, 2013). The conversion of natural vegetation to cropland and deforestation usually leads to loss of carbon storage in soils (Poeplau et al., 2011). Also, the use of some pesticides, dominantly herbicides can increase the emission of CO_2 from the soil (Kara et al., 2004).

Anthropogenic soils are formed by human activity whose diagnostic horizons are significantly modified or destroyed (Capra et al., 2014). Anthropogenic soils, more precisely Anthrosols cover more than 500.000 ha in north-western Europe (IUSS Working Group WRB, 2015). Nine-year research which was carried out in the northern Germany showed that Luvisol had lower microbial activity compared to Anthrosol (Dilly et al., 2003). Also, previously published research showed that the CO_2 flux from urban soils is predominantly greater than the one originated from natural soils (Sarzhanov et al., 2015; Sarzhanov et al., 2017).

The sustainable management of pedunculate oak (*Quercus robur* L.) forests refers to the successful regeneration of oak stands, as well as maintenance and protection of stands, especially in younger developmental stages (Rađević et al., 2020). The aim of this study was to examine whether the anthropogenic activity during silvicultural treatments has an impact on the increment of CO_2 flux during summer period.

MATERIALS AND METHODS
MATERIJALI I METODE

The research was carried out in the Srem region, Autonomous Province of Vojvodina, Republic of Serbia (45º2’10.06” N, 19º13’1.29” E), (Figure 1). In this country, pedunculate oak forests (*Quercus robur* L.) cover about 32 400 ha, whereas the share of *Quercus robur* L, in total volume of growing stock, is 2.5%. The largest complex of these forests is situated in the Srem region, along the left bank of the Sava River, where pure and mixed forests of pedunculate oak are formed. In this region, alluvial hydrophilic floodplain oak forests are even-aged, but are also in different developmental stages (Banković et al., 2009).

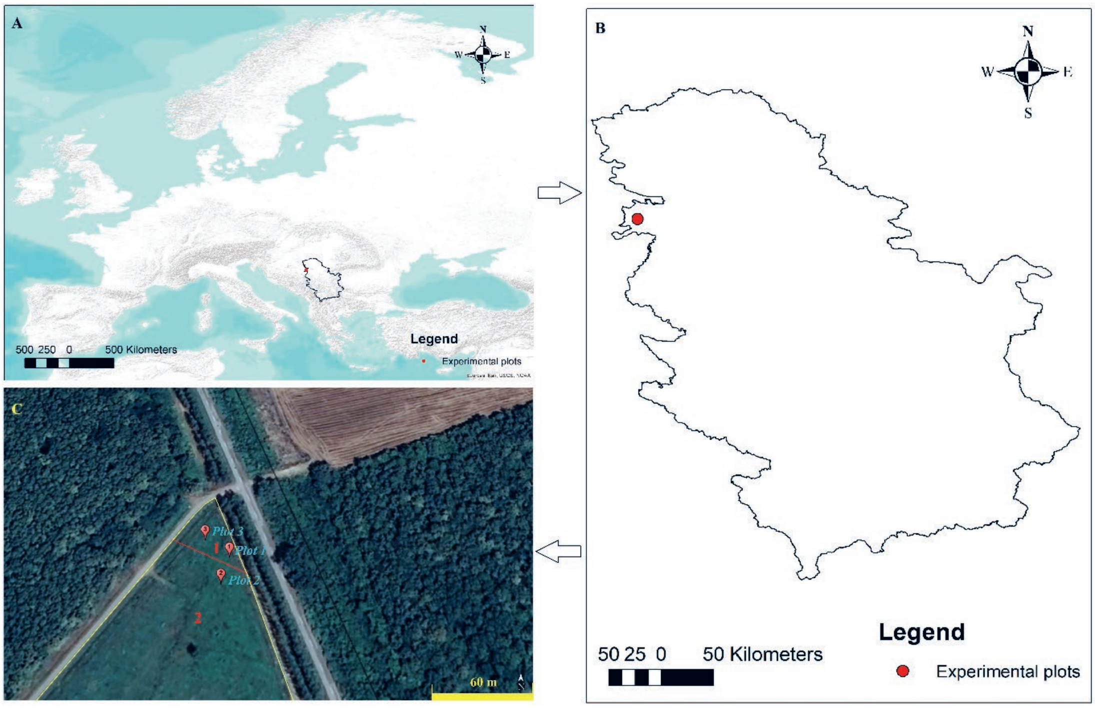

Figure 1. The geographical location of the research area in the study.
Slika 1. Geografski položaj područja istraživanja

Pedunculate oak and other forest species form different plant communities in the area of Srem such as: communities of pedunculate oak and narrow-leaved ash (*Fraxino angustifoliae-Quercetum roboris* Jov. et Tom. 1979.), then monodominant pedunculate oak forests (*Genisto elatae-Quercetum roboris* Horv. 1938.), communities of pedunculate oak, narrow-leaved ash and hornbeam (*Carpino-Fraxino-Quercetum roboris* Miš. et Broz 1962.). On the other hand, the associations of pedunculate oak and hornbeam (*Carpino-betuli-Quercetum roboris* Anić 1959.), as well as phytocenoses of pedunculate oak, hornbeam and Turkey oak (*Carpino betuli-Quercetum roboris quercetosum cerris* Rauš 1969.) are related with zonal vegetation (Tomić and Jović, 2002; Tomić, 2004). Appropriate silvicultural treatments are carried out based on the features of stand's development stages. Planned rotation length of the pedunculate oak is 160 years. (Rađević et al., 2020). Considering ecological conditions, soil type, rotation period, and type of stand regeneration, the area of these forests is convenient to examine the influence of forest management on CO_2 emission from soils.

The data of climate characteristics of research area was obtained from the Republic Hydrometeorological Service of Serbia (https://www.hidmet.gov.rs/) for the observation period from 1991 to 2020. The average annual temperature in the research area was 11.8 °C, while the absolute maximum temperature was 40.7 °C. The precipitation in the vegetation period (April-September) amounted to 355.5 mm i.e., 57.6% of the average annual precipitation (617.1 mm). The average monthly temperature was the highest in July (22.1 °C), whereas the largest amount (75.4 mm) of precipitation was recorded in June. The mean annual relative humidity is 76.4%.

Three plots, dimensions of 5x5m, have been chosen for research within the alliance of *Alno-Quercion roboris* Horv. 1938. in the Srem region. Experimental plots were situated within the regeneration area of oak stand in a non-flooded zone managed by public enterprise "Vojvodinašume". All phases of regeneration cutting were carried out on this area, more precisely, all mature trees were removed, while the acorn sowing was conducted in 2020. The regeneration area of oak stand is divided on two parts (Figure 1C). The first smaller part (1) was not under pesticide treatments, while the rest of the stand was treated. In order to conduct the successful regeneration of pedunculate oak, the pesticides application was performed on the second greater part (2) of stand. During 2018-2020, before the acorn sowing, this part of stand was treated with Triclopyr and Glyphosate. The systemic selective herbicide (Nicosulfuron) and Propiconazole fungicide were applied after the sowing within the regenerated stand**.** Two plots were established within the first part of the stand, while the one plot was within the second part of the stand. The distance between experimental plots was about 25m (Figure 1C). The plots were located about 40m from the main road. Between the regenerated stand and road there is the poplar (*Populus x euroamericana* (Dode) Guinier)) buffer strip. Considering the plots are established close to each other, microclimatic conditions were uniform on all experimental plots. The values of soil temperature and soil water content were measured during the air sampling (Figure 3), and the average monthly temperature and amount of precipitation were obtained from the nearest weather station (Sremska Mitrovica) for study period (https://www.hidmet.gov.rs/), (Table 1).

Table 1. Average monthly temperature and precipitation during the summer period in 2021.

Tablica 1. Srednje mjesečne temperature i oborine tijekom ljetnog razdoblja 2021. godine

	VI	VII	VIII
Average monthly temperatures	22.7	22.4	21.4
Precipitation	7.2	105.9	30.1

The soil pits were dug on each experimental plot. The World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) was used for the identification of three soil profiles. The soil samples were taken from topsoils (0-10 cm depth) in each of three profiles and used for determination of physico-chemical properties of soils. Particle size distribution (%) was determined by the international B-pipette method with the preparation in sodium pyrophosphate. Based on particle size distribution, soil textural classes were determined using Atteberg's classification. Kopecky's cylinders (volume of 100cm^3) were used for the determination of soil bulk density (Bošnjak et al., 1997). Soil pH value was measured electrometrically using pH meter apparatus. The determination of organic carbon content was performed on the Elementar Vario EL III, while the $CaCO_3$ content was determined volumetrically using Scheibler calcimeter. Physico-chemical properties of soils are shown in Table 2 for each plot.

Table 2. Physico-chemical properties of soils within experimental plots.

Tablica 2. Fizičko-kemijska svojstava tla na pokusnim plohama

	Bulk density g/cm^3	Total sand %	Silt + Clay %	Textural class	C %	$CaCO_3$ %	pH (H_2O)
Plot 1	1.45	24.7	75.3	clay loam	0.929	7.57	7,78
Plot 2	1.04	26.7	73.3	clay loam	4.056	0.04	7,21
Plot 3	1.34	24.8	75.2	clay loam	0.110	0.50	7,65

Figure 2. Soil profiles within the experimental plots. A-Gleysol (*Plot 1*); B-Gleysol (*Plot 2*); C- Anthrosol (*Plot 3*).
Slika 2. Profili tla na pokusnim plohama. A-Gleysol (*Plot 1*); B-Gleysol (*Plot 2*); C- Anthrosol (*Plot 3*).

Within the first plot (*Plot 1*) there was no anthropogenic influence, so this plot was defined as the control plot, while the treatment of pesticides was previously carried out on the second plot (*Plot 2*) during regeneration period. According to Rađević et al. (2020), on this plot, the pesticides application was conducted in order to protect oak seedlings from weeds, different pests and diseases. Rapid growth of weed vegetation can have adverse effects on the natural regeneration of oak stands (Posarić, 2010; Vasić et al., 2014; Vasić et al., 2022). Pesticide treatments were performed in accordance with the FSC policy (Rađević et al., 2020). The main goal of pesticides application was a successful regeneration of oak stands. Both plots (*Plot 1 and Plot 2*) were placed on natural soils. Based on the morphological features of the observed soil profiles, Gleysol was detected within the first and the second plot (Figure 2A and Figure 2B). The third location (*Plot 3*) was established on the anthropogenic soil, where the treatment of pesticides was not conducted. On the third plot, Gleysol as natural soil was under considerable anthropogenic influence, which diagnostic horizons are significantly altered and modified. Therefore, this soil type was determined as Anthrosol (Figure 2C). This soil type was formed during a site preparation for regeneration of stand. Soil organic carbon content in topsoil (0-10 cm depth) at *Plot 1*, *Plot 2* and *Plot 3* ranged from 0.93%, 4.1% and 0.11%, respectively. Ratio between CO_2 flux and carbon stock is widely used parameter for determination of carbon sustainability in soil (Sarzhanov et al., 2017).

The total soil respiration (autotrophic and heterotrophic respiration) was measured using the closed chambers method. According to Schindlbacher et al. (2009) the contribution of autotrophic soil respiration to total soil respiration is the greatest in summer period. The field observation of CO_2 emission was conducted during summer season (Jun, July and August) in 2021. The air sampling was performed using soil respiratory chambers (Avilov et al., 2014). The plastic base of each chamber was installed in the soil at the depth of 10 cm within each plot. The installation of bases was done two weeks before observation period in order to stabilize fluxes after soil disturbance (Buchmann, 2000). The first air sampling was carried out two weeks after insertion of bases to minimize the influence of severed fine roots on soil respiration (Laganière et al., 2012). Before sampling, the cylindrical chambers were attached on the top of the base, in hermetic condition. The air inside the chambers was homogenized by small fan, fixed at the top of the chamber. During sampling period, five chambers were placed at each plot. Gas extraction valve was installed on the chamber, and the sampling of air was carried out with a medical syringe. Three air samples were taken from each chamber. The air was sampled at 15, 30 and 45-min intervals (Heinemeyer and McNamara, 2011; Ming et al., 2018), after placing the chambers on the bases. Air samples were injected into glass vials and sent to the laboratory for analyses. The sampling was conducted at each plot once in every ten days. Samples collection was performed from 8:00 a.m. to 9:00 a.m. (five times during the season) as well as between 12:00 p.m. and 13:00 p.m. (two times during the season). Sampling was carried out at the same time on all experimental plots. Collected samples were analysed using the gas chromatograph Agilent 8890 (Agilent Technologies, Santa Clara, California, USA). A total of 315 samples was collected and analysed. CO_2 flux was calculated for each plot using the formula according to Ming et al. (2018) based on the linear increase of the gas concentration inside closed chambers during the sampling time. The average values of CO_2 flux were obtained based on values of emissions from five chambers placed within each plot. The obtained values of flux are expressed in g CO_2 m^{-2} per day (Sarzhanov et al., 2015).

During the air sampling, soil temperature was measured by soil thermometer at the depth of 5 cm. Soil moisture content was determined by gravimetric method. The soil samples were taken and put into aluminium tins. Afterwards, the samples were dried to constant weight in the oven at the temperature between 103-105 °C.

The relationship between CO_2 emission, soil temperature and soil water content was analysed through Pearson's correlation test, simple and multiple linear regressions. Statistical analysis of the obtained data was carried out by Statistica 12 program package and R statistical software. Microsoft Exel 2016, "ggplot2" (Version 3.3.2), (Wickham, 2016) and "scatterplot3d" (Version 0.3-41), (Ligges and Mächler, 2003) packages in the R environment were used for the graphic design.

RESULTS
REZULTATI

Soil temperature at the depth of 5 cm and soil water content are given in Figure 3. The values of soil temperature and soil water content were changing distinctly during the research period. The highest soil temperature values were recorded on the 14th of July (34 °C) and 4th of August (33 °C), (Figure 3). The lowest soil temperature was measured at the beginning of the research period. The soil water content ranged from 4.81% to 30.32%. The decrease of soil water content was followed by an increase of soil temperature. Sharp decline of soil moisture was recorded when the highest values of soil temperature were measured (Figure 3). The inverse correlation was found between soil temperature and soil moisture ($r = -0.533$, $p < 0.05$), where after a rainfall, soil water content was considerably increased and affected the reduction of soil temperature.

Soil respiration at *Plot 1, Plot 2 and Plot 3* ranged from 4.28-10.86 g CO_2 m^{-2} day^{-1}, 5.22-17.96 g CO_2 m^{-2} day^{-1} and 3.60-15.29 g CO_2 m^{-2} day^{-1}, respectively (Figure 4). At the beginning of study period, the emission of CO_2 within the second plot (*Plot 2*) was slightly higher than CO_2 emission within the third plot (*Plot 3*), while CO_2 flux within the control plot (*Plot 1*) was the lowest. At the end of June, the greatest value of flux was recorded on *Plot 3* and was higher for 40% compared to other two plots. The values of soil respiration were similar on 2nd of July at all three plots. In the middle of July, soil respiration from *Plot 3* was greater compared to the other research plots, while the highest value of flux was recorded in the last decade of July within the second plot. The study showed that the greatest difference in the CO_2 emission between plots was recorded on 4th of August when the value flux on the third plot was over 50% higher than on *Plot 1* and *Plot 2*. At the end of the study period, the values of CO_2 flux were very similar within all experimental plots. During sampling period, the greatest value of CO_2 emission was measured at *Plot 2*, while the values of CO_2 flux were very similar in the middle of July and in the first decade of August within the third location. The emissions of CO_2 within the control plot were predomi-

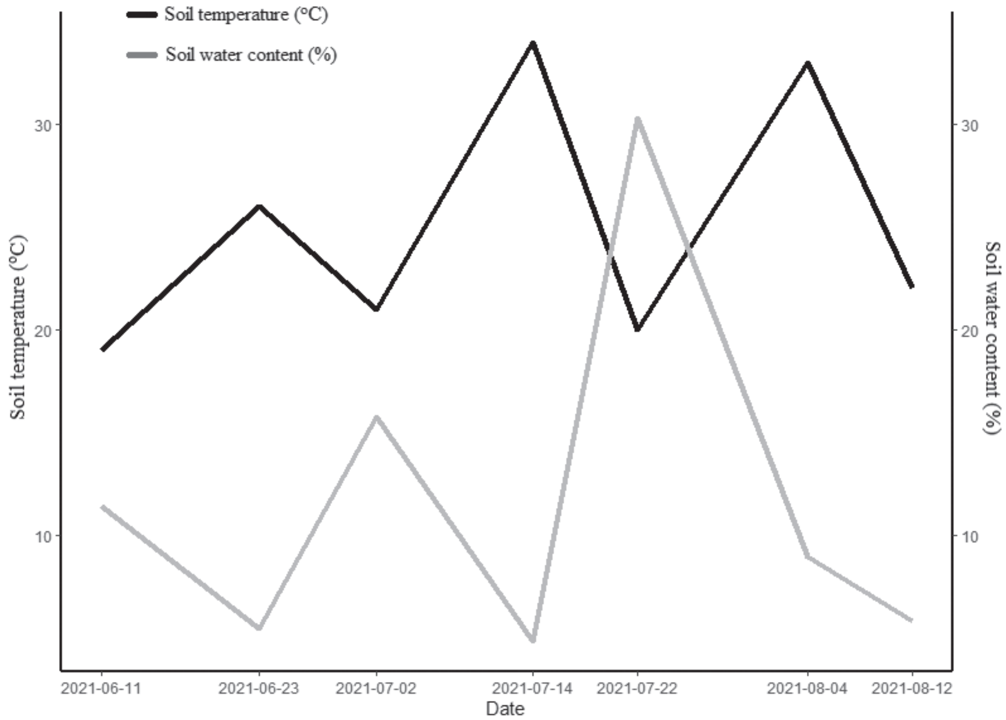

Figure 3. Dynamics of soil temperature (°C) and soil water content (%) during the summer period in 2021.
Slika 3. Dinamika temperature tla (°C) i sadržaja vode (%) u tlu tijekom ljetnog razdoblja 2021. godine

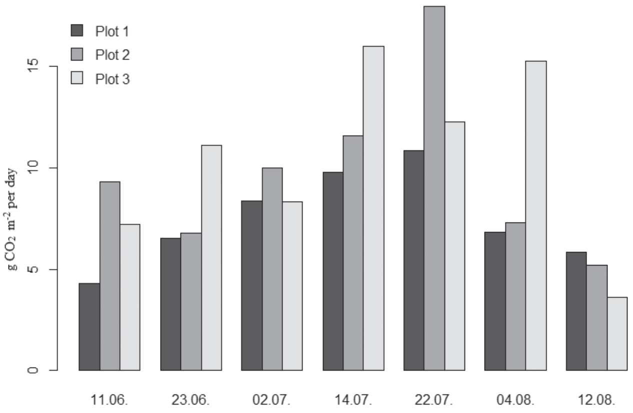

Figure 4. Average daily CO_2 emissions (g CO_2 m^{-2} day^{-1}) from soils for each plot during the summer season in 2021.
Slika 4. Prosječna dnevna emisija ugljikovog dioksida (g CO_2 m^{-2} dan^{-1}) iz tla za svaku parcelu tijekom ljetnog razdoblja 2021. godine

nantly lower compared to the other two plots during the summer season.

The two-month-long monitoring during summer within survey plots showed that the variability of seasonal dynamics of the soil respiration usually depends on the changes in soil temperature and moisture (Figure 5). Within the *Plot 1* and *Plot 2*, the most important environmental driver which affected the CO_2 flux was soil water content. High positive correlation was found for the CO_2 flux with soil moisture ($r = 0.85$, $p < 0.05$) within the second plot, while moderate correlation was observed within the first plot ($r = 0.55$, $p < 0.05$). At the same time, low correlation was revealed with the soil temperature within both plots. Considering the third plot, reliable positive correlation was observed with the soil temperature ($r = 0.77$, $p < 0.05$), while no correlation was found among the CO_2 flux and the soil moisture ($r = 0.05$). During the survey season, the average emission of CO_2 within the control plot (*Plot 1*) was increasing until the last decade of July. The CO_2 flux reached the maximum value at the same time when the greatest value of soil water content was recorded, then the emission of CO_2 began to decrease gradually until the end of the summer season. Similar dynamic of CO_2 flux was observed within the second plot (*Plot 2*), but changes of soil moisture more significantly affected the emission compared to the control plot. The slight decline of the CO_2 emission at the beginning of the season was followed with the decrease of soil water content. From the last decade of June, the values of flux were increasing and have reached the maximum on the 22nd of July. Due to the increase of the soil temperature that caused the reduction of soil water content, a rapid drop of CO_2 emission happened. It reached to the minimum value (5.22 g CO_2 m^{-2} day^{-1}) at the end of the observation period. Within the both plots (*Plot 1 and Plot 2*), the CO_2 flux had different values when soil water content was low (about 5%). In that case, the increased soil temperature caused the greater emission. The most significant factor within the third plot (*Plot 3*) affecting the CO_2 flux was the soil temperature. The greatest values of the flux were recorded in the middle of July and during the first decade of August when the soil temperature was over 30 °C. All decreases of

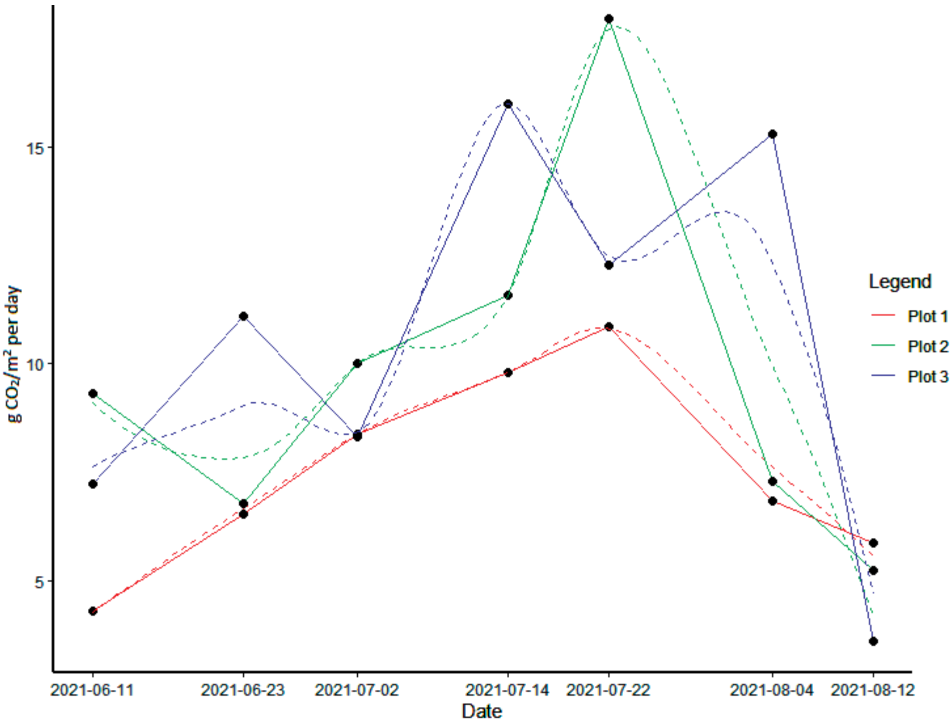

Figure 5. Dynamics of CO_2 emissions during the summer period in 2021.
Slika 5. Dinamika emisije ugljikovog dioksida (CO_2) tijekom ljetnog razdoblja 2021. godine

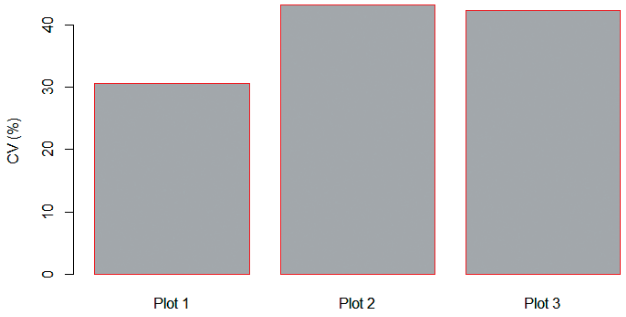

Figure 6. Coefficient of variation (%) for soil respiration.
Slika 6. Koeficijent varijacije (%) za disanje tla.

the soil temperature were followed by the reduction of CO_2 emission. With soil temperature of 21±2 °C, soil water content had additional effect on the CO_2 flux, where the values of flux were greater when soil moisture was increased. Obtained values of the flux on each plot were low at the end of the observation period, since soil temperature and soil moisture were significantly reduced.

The coefficient of variation for CO_2 flux is illustrated in Figure 6 for each plot. The average emission varied the least (CV = 30.64%) within the control plot, while the greatest value of coefficient of variation (CV) was detected within the *Plot 2* (43.23%). Similar variation around the middle value (CV = 42.40%) was obtained within the third plot. The plots which were under the anthropogenic influences had generally higher emission compared to the control plot. The greatest average value of CO_2 flux as well as the least organic carbon content in anthropogenic soil indicate that the stability of the organic carbon is very low compared to Gleysol (*Plot 1* and *Plot 2*).

The simple linear relationship of soil respiration and soil temperature at the depth of 5 cm for each plot is shown in Figure 7. The coefficient of determination (R^2) ranged from 0.04 to 0.60, whereas the greatest value of R^2 is obtained for the *Plot 3*. Reliable relationships between CO_2 flux and soil water content were observed within the *Plot 1* and *Plot 2* ($R^2 = 0.30$ and $R^2 = 0.72$, respectively), (Figure 8). Soil mo-

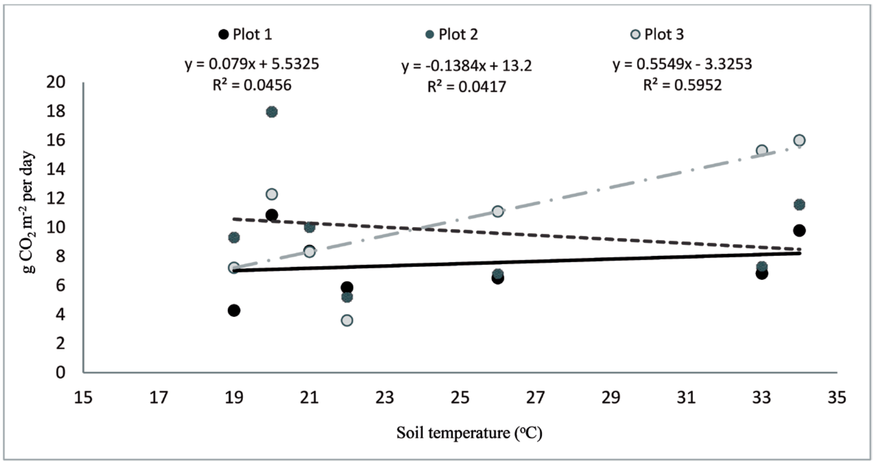

Figure 7. Relationship between soil respiration (g CO_2 m^{-2} day^{-1}) and soil temperature at the 5cm depth (°C).
Slika 7. Odnos između respiracije tla (g CO2 m^{-2} dan^{-1}) i temperature tla na dubini od 5 cm (°C)

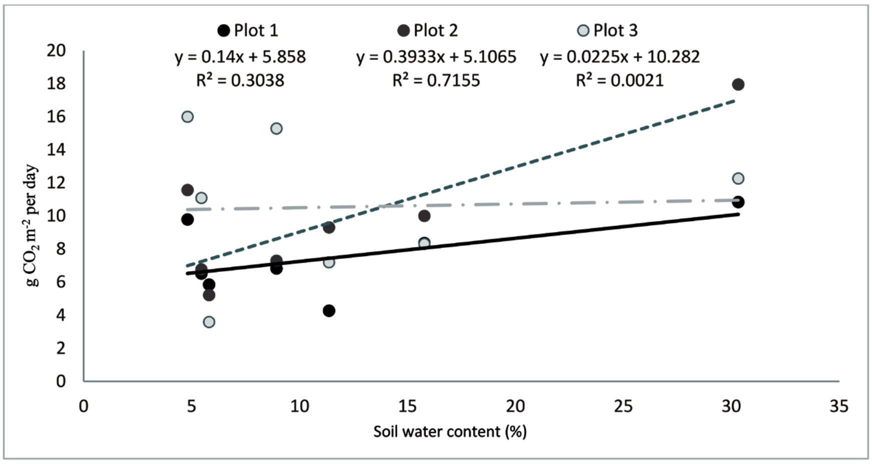

Figure 8. Relationship between soil respiration (g CO_2 m^{-2} day^{-1}) and soil water content (%).
Slika 8. Odnos između respiracije tla (g CO_2 m^{-2} dan^{-1}) i sadržaja vode u tlu (%)

Table 3. Empirical equations developed from multiple linear regression analysis and R2 values.

Tablica 3. Empirijske jednadžbe razvijene multilinearnom regresijskom analizom i R2 vrijednosti

Experimental plots	Model	R^2
Plot 1	Sr = -1.8278 + 0.2622 St + 0.2360 Swc	0.66
Plot 2	Sr = -1.7293 + 0.2332 St + 0.4786 Swc	0.80
Plot 3	Sr = -13.1514 + 0.7994 St + 0.3150 Swc	0.89

Legend: Sr-Soil respiration (g CO_2 m^{-2} day^{-1}); St-Soil temperature (°C); Swc-Soil water content.

isture was the dominant factor affecting the CO_2 emission from natural soil, but its influence was stronger on the plot where the treatment of pesticides was carried out. With the rise of soil moisture, the plot that was under the influence of pesticides had more intensive increase of the CO_2 emission in comparison to the control plot.

For each plot, multiple linear regression models were obtained for CO_2 flux as a function of soil temperature and moisture (Figure 9). The best multiple linear regression model was found for the third plot ($R^2 = 0.89$), whereas the lowest value of R^2 amounted to 0.66 and was obtained within control plot (Table 3). Furthermore, the significant value of coefficient of determination ($R^2 = 0.80$) was determined for the *Plot 2*. Multiple linear regression showed that the CO_2 emission from the soil was primarily controlled by soil moisture within the plots on natural soil, while the effect of soil temperature, as a secondary factor, was weaker for the second plot. For the anthropogenic soil, temperature of soil was dominant factor affecting the CO_2 flux. However, soil water content as additional factor of emission had stronger effect in comparison to the soil temperature within the plot which was under treatment of pesticides.

DISCUSSION
RASPRAVA

Soil temperature and water content are the most responsible environmental drivers which affect the variation of car-

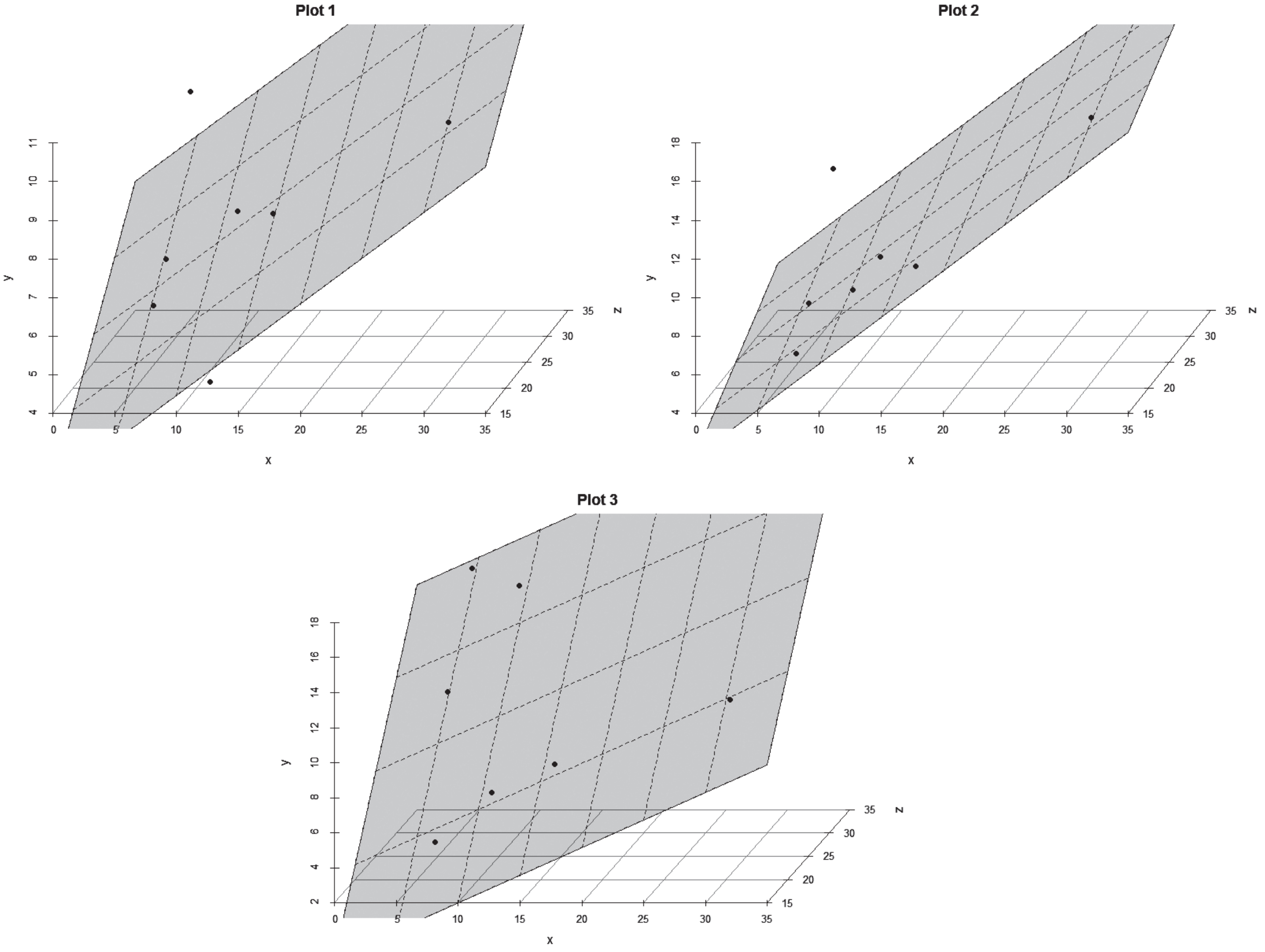

Figure 9. Combined effect of soil temperature and water content on soil respiration for each experimental plot. Y-axis (soil respiration (g CO_2 m^{-2} day^{-1})); X-axis (soil water content (%)); Z-axis (soil temperature (°C)).

Slika 9. Kombinirani učinak temperature tla i sadržaja vode u tlu na disanje tla za svaku pokusnu plohu. Y-os (disanje tla (g CO_2 m^{-2} dan-^{1})); X-os (sadržaj vode u tlu (%)); Z-os (temperatura tla (°C)) bon dioxide emission from soil (Adachi et al., 2006). The results of the the presented study show that soil temperature and moisture had different influence on the CO_2 flux, also depending on the anthropogenic and environmental factors. The influence of topography and vegetation cover can be very important for soil respiration rate, since they significantly affect microsite factors, such as soil temperature and soil moisture (Li et al., 2008). Also, silvicultural treatments can change the microclimate conditions of the stand (Ma et al., 2010). The effect of thinning the forest stand contribute to the evapotranspiration increment within the ecosystem (Boczoń et al., 2016). During the last phase of regeneration cutting of pedunculate oak, all mature trees were removed. Consequently, it enabled larger quantity of sunlight and rainfall to reach the surface of the soil. The negative correlation between soil temperature and soil water content was detected in temperate mixed hardwood forest in central Massachusetts (Davidson et al., 1998). Increased insolation had an influence on a quick warming of soil as well as more intensive soil evaporation, while rapid drop of soil water content was recorded due to the rise of soil temperature.

Within the various type of soils, soil temperature and soil moisture can have different influence on soil respiration, where one of these two factors can be more dominant than another (Koizumi et al., 1999). Presented results showed that CO_2 flux gave different responses to soil temperature and moisture within various type of soil. The soil water content was dominant driver in natural soils, but for the anthropogenic soil, the main limitation factor of the CO_2 emission was soil temperature.

In deciduous and coniferous forests, the contribution of soil respiration to total ecosystem respiration varied during different seasons (Curiel Yuste et al., 2005). The variation of CO_2 emission was pronounced during the summer period, especially within the plots that were under the anthropogenic influence. Tang et al. (2006) suggested that within successional forests, CO_2 flux was significantly lower during the cool and dry season, compared to the hot and humid one. Our study was carried out during the warmest period of the year. At the beginning, as well as at the end of the observation period, the low values of CO_2 flux appeared as consequence of decreased temperature and moisture of the soil.

Some pesticides can intensify CO_2 emission from the soil, whereas others reduce it, or do not have any effect (Jezierska-Tys et al., 2021). Herbicides which were used to control broadleaf weeds in agricultural crops caused significant raise of CO_2 emission from the soil during the two-year study (Shi et al., 2020). Glyphosate, widely used herbicide in agriculture, stimulated microbial activity which resulted in increased soil respiration (Araújo et al., 2003). The application of herbicides in the regeneration of oak forests such as nicosulfuron, imazamoxare and cycloxydim can cause an increase in number of actinomycetes and fungi (Vasić et al., 2018). The largest part of heterotrophic respiration from the soil is evolved by microorganisms, so they are the one of the most important agents in the soil which produce CO_2 (Kuzyakov, 2005). For dry habitats, such as steppes, precipitation is limiting factor which affects soil microbial respiration. Soil heterotrophic respiration in these regions is being increased with the rise of precipitation (Zhao et al., 2016). The increased emission of CO_2 within the plot which was under the influence of pesticides (*Plot 2*) application compared to the control plot (*Plot 1*) can be explained by stimulating effect of pesticides on the microbial activity in the soil. Furthermore, within *Plot 2*, more intensive increase of the CO2 flux was recorded with the rise of soil water content in comparison to *Plot 1*.

The average value of CO_2 emission from urban soil was 20 g CO_2 m^{-2} day^{-1} in Beijing (China) (Fu et al., 2013), whereas 17 g CO_2 m^{-2} day^{-1} was recorded in Boston (USA) (Decina et al., 2016). However, Sarzhanov et al. (2017) suggested that CO_2 emission from urban soil was substantially greater in comparison to Chernic Phaeozem (natural soil), which is the result of low sustainability of organic carbon in the urban soil. Our study showed similar results, where the CO_2 flux from anthropogenic soil (*Plot 3*) was higher compared to the natural soil (*Plot 1*). High soil temperatures caused emissions which were approximately equal to the emissions in the urban environments. It indicates that the modification of soil in natural ecosystems can induce a similar emission of CO_2 like in urban areas.

CONCLUSION
ZAKLJUČAK

The change of microsite conditions due to the trees removal in the last phase of regeneration cutting had a very important influence on the key drivers of emission (soil temperature and soil moisture). The plots which were under anthropogenic influence (*Plot 2* and *Plot 3*) had predominantly higher values of CO_2 flux compared to the control plot (*Plot 1*) during the observation period.

The soil temperature and moisture as the most dominant factors of the emission had various impact on the soil respiration depending on the soil type. The main limitation factor of emission within natural soils (Gleysol), (*Plot 1* and *Plot 2*) was soil water content, whereas CO_2 flux from anthropogenic soil (Anthrosol), (*Plot 3*) was primarily controlled by the soil temperature. The simple linear models showed that the strongest relationship was obtained between CO_2 emission and the soil water content within the plot where the treatment of pesticides was conducted (*Plot 2*), while the best multiple linear regression model for CO_2 flux as a function of the soil temperature and moisture was found for the third plot (*Plot 3*).

Our study showed that the plot which was exposed to the treatment of pesticides (*Plot 2*) had more intensive increase of the CO_2 flux with the rise of soil moisture compared to control plot (*Plot 1*). Also, due to the low stability of organic carbon in anthropogenic soil (*Plot 3*), higher CO_2 emission from this soil type was recorded in comparison to the reference natural soil (*Plot 1*) during the summer period.

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SAŽETAK

Gubitak organskog ugljika i povećana emisija ugljikovog dioksida (CO_2) iz tla uzrokovani su raznim ljudskim aktivnostima. Cilj ovoga rada bio je ispitati antropogeni utjecaj na emisije ugljikovog dioksida iz tla tijekom obnove sastojine hrasta lužnjaka (*Quercus robur* L.). Istraživanje je provedeno u Sremskom okrugu (Autonomna Pokrajina Vojvodina, Republika Srbija) tijekom ljeta 2021. godine (Slika 1). Postavljene su tri pokusne plohe, od kojih je na dvije primjetan antropogen utjecaj. Prva ploha (*Plot 1*) osnovana je na prirodnom tlu (Gleysol), (Slika 2A) i nije bila izložena antropogenom utjecaju, dok je druga (*Plot 2*) osnovana na istom tipu tla (Slika 2B) na kojem je obavljeno tretiranje pesticidima zbog zaštite hrastovog pomlatka tijekom procesa obnove sastojine. Treća ploha (*Plot 3*) je osnovana na antropogenom tlu (Anthrosol), (Slika 2C), koje je nastalo uslijed pripreme staništa za obnovu sastojine, bez tretiranja pesticidima. Uzorci zraka prikupljeni su pomoću cilindričnih komora, dok su analize obavljene na plinskom kromatografu (Agilent 8890).

Dinamika temperature i vlažnosti tla kao najvažniji čimbenici (Slika 3) značajno su utjecali na emisiju ugljikovog dioksida tijekom ljetnog razdoblja. Na plohi na kojoj je formirano antropogeno tlo, dobivena je pouzdana pozitivna korelacija između protoka ugljikovog dioksida i temperature tla ($r = 0.77$, $p < 0.05$), dok je visoka značajna korelacija između protoka i vlažnosti tla dobivena na prirodnom tlu koje je bilo pod utjecajem pesticida ($r = 0.85$, $p < 0,05$). Plohe koje su bile pod antropogenim utjecajem (*Plot 2* i *Plot 3*) imale su veće vrijednosti toka tijekom ljetnog razdoblja u odnosu na prvu plohu (*Plot 1*) (Slika 4) i (Slika 5). Prosječna emisija najmanje je varirala (CV = 30.64%) na prvoj plohi (*Plot 1*), dok je najveća vrijednost koeficijenta varijacije (CV) zabilježena na drugoj plohi (43.23%), (Slika 6). Vrijednosti koeficijenta determinacije (R^2) u običnoj linearnoj regresiji, gdje je prikazana ovisnost između protoka ugljikovog dioksida i temperature, bile su u rasponu od 0.04 do 0.60, a najveća vrijednost dobivena je na trećoj plohi (Plot 3) (Slika 7). Na plohama koje su bile postavljene na prirodnom tlu (*Plot 1* i *Plot 2*) emisija ugljikovog dioksida uglavnom je ovisila o vlažnosti tla. S povećanjem vlažnosti tla, ploha koja je bila pod utjecajem pesticida (*Plot 2*) imala je intenzivniji porast emisija u odnosu na prvu plohu (*Plot 1*), (Slika 8). Najbolji multilinearni regresijski model, gdje je ispitivan kombinirani učinak temperature i vlažnosti tla na emisiju ugljikovog dioksida, dobiven je na trećoj plohi (Slika 9), gdje je vrijednost koeficijenta determinacije (R^2) iznosila 0.89 (Tablica 3).

Kao posljedica primjene pesticida, kao i stvaranja antropogenog tla tijekom obnove hrastove sastojine, došlo je do značajnog povećanja emisije ugljikovog dioksida (CO_2) iz tla u odnosu na referentno prirodno tlo bez antropogenog utjecaja.

KLJUČNE RIJEČI: CO_2, hrast lužnjak, antropogeni utjecaj, temperatura tla, vlažnost tla