Topola Poplar SINCE 1957

OPEN ACCESS

DOI: 10.5937/topola2516053N
UDC: 630*9(497.113)

Original scientific paper

Abiotic factors impact on soil respiration

Boris Najdovski[1*], Kristijan Cokoski[1], Kole Vasilevski[1], Nikolco Velkovski[1]

[1] Ss. Cyril and Methodius University in Skopje. Hans Em Faculty of Forest Sciences, Landscape Architecture and Environmental Engineering, Skopje, North Macedonia

* Corresponding author: Boris Najdovski; E-mail: najdovski@sf.ukim.edu.mk

Received: 7 November 2025; **Revised:** 21 November 2025; **Accepted:** 22 November 2025

Abstract: Soil respiration describes the process of gas exchange between organisms and their environment. As one of the key processes in ecosystems, soil respiration is linked to ecosystem productivity, soil fertility, and the regional and global carbon cycles. The objective of this study is to investigate the impact of abiotic factors, particularly variations in air temperature and humidity, on the intensity of soil respiration in the dystric cambisols within the *Quercetum montanum typicum* forest community at the National Park "Fruška Gora" in the Vojvodina Province of Serbia. A total of 32 site visits were conducted in 2014–2017 period to obtain site-specific data on air and soil temperature and humidity, and soil evaporation and respiration. The key findings indicate that the variations in air temperature and humidity significantly impact soil respiration. In most cases, soil respiration positively correlates with soil temperature; however, in some years, a nonlinear response has been observed, which may indicate thermal stress at higher temperatures.

Keywords: abiotic factors, temperature, humidity, soil respiration.

1. Introduction

Soil is generally described as a mixture of dead organic matter, air, water, and mineral particles that support plant growth (Buscot, 2005). The word *respiration*, derived from the Latin prefix *re-* (meaning "back" or "again") and the root *spirare* (meaning "to breathe"), literally signifies "to breathe again and again". Soil respiration represents a process within ecosystems during which CO_2 is released from the soil through root respiration, microbial decomposition of various residues and organic matter, and the respiration of soil fauna, while the organisms in the soil obtain energy for life processes through the catabolism of organic matter. This definition describes the process of gas exchange between organisms and their environment and therefore it is logical to speak of soil as something that can "breathe".

Soil respiration is also defined as the production of carbon dioxide by organisms and plant components within the soil. Through the carbon cycle, CO_2 is produced by plant respiration (Rp) and microbial respiration (Rm), which occurs during the decomposition of plant residues and soil organic matter. Plant respiration (Rp), also known as autotrophic respiration, can be further divided into aboveground plant respiration (Ra) and belowground plant respiration (Rb). The efflux rate measured at the soil surface (Rs) represents the sum of root respiration and microbial respiration, expressed as Rs = Rb + Rm (Lloyd and Farquhar, 1996). A higher intensity of microbial respiration (Rm) indicates greater dehydrogenase enzyme activity (DHA) and more intensive mineralization of fresh organic matter and humus (Govedarica and Jarak, 1995).

As one of the key processes in ecosystems, soil respiration is linked to ecosystem productivity, soil fertility, and the regional and global carbon cycles. Global warming is expected to stimulate soil respiration and reduce the total carbon content in the planet's ecosystems (Raich and Schlesinger, 1992). Forests act as carbon sinks when they absorb more carbon than they release. Conversely, forests can also function as carbon sources when they emit more carbon than they absorb, resulting in a net carbon emission. Since 1990, forests worldwide have annually removed approximately 30% of global CO_2 emissions from the atmosphere, originating from fossil fuel combustion, cement production, and land-use changes such as deforestation (Pan et al. 2011). Since the global carbon cycle regulates climate change, soil respiration also becomes relevant to climate change, carbon exchange, and environmental protection policies. Because of the capacity of forests to retain and store substantial amounts of carbon, the forestry sector has the potential to mitigate climate change. Therefore, reducing forest carbon sources and enhancing carbon sequestration in forests represent important objectives for mitigating the effects of climate change at the national, regional, and continental levels.

Fruška Gora, located in northern Serbia, represents a typical temperate forest ecosystem of the Balkan region, characterized by moderate continental climate and diverse deciduous vegetation.

Several previous studies have investigated soil respiration in the forest soils of Fruška Gora (Janković and Stefanović, 1969; Stefanović, 1985; Pilipović et al. 2011). According to the study by Janković and Stefanović (1969), regarding the seasonal dynamics of CO_2 production, the release of this gas is particularly high in June and July, followed by a sharp decline in August. Subsequently, CO_2 emission increases again in September, while from October onward, another decrease occurs. Furthermore, the same authors concluded that CO_2 release is higher during the night.

Stefanović (1985) discovered that soil plays a significant role in CO_2 formation processes, noting that in strongly leached luvisols, the intensity of CO_2 release is lower compared to dystric cambisols.

The study by Pilipović et al. (2011) demonstrated considerable diurnal variations in soil respiration, which closely follow air and soil temperature, as well as soil moisture content. In addition, the author concluded that soil moisture has a smaller impact on annual variations in soil respiration, but its seasonal impact is strongly expressed from July to September, when soil respiration tends to decrease. Soil respiration shows a nonlinear correlation with soil moisture content, with the highest respiration intensity recorded at 0.25 m^3/m^3. Both higher and lower moisture levels resulted in reduced respiration rates. According to this study, the intensity of soil respiration is higher in mixed forest stands than in monospecific stands.

Considering the effect of climate change on forest ecosystems, the objective of this study is to investigate the impact of abiotic factors, particularly variations in air temperature and humidity, on the intensity of soil respiration.

2. Material and methods

2.1. Study area

This study is set in a *Quercetum montanum typicum* forest community that is a coppice forest of Sessile oak (*Quercus petraea* (Matt.) Liebl.) with an admixture of Beech (*Fagus sylvatica* L.). The site of investigation is situated in department 20/c, Management unit Popovica-Majdan-Zmajevac, NP "Fruška Gora" (coordinates 45°09′24.00″ N, 19°48′38.80″ E), Republic of Serbia. Moderately steep terrain, southeast exposure, 480–500 m elevation, schist geological base, and dystric cambisols characterize the area.

2.2. Data collection

All measurements and analyses were performed following standardized protocols for soil gas exchange and moisture determination, described in the soil testing manuals of the Yugoslav Soil Testing Society (Cencelj, 1966; Racz, 1971; Bošnjak et al. 1997; Kastori et al. 2006).

A 25 × 25 m sample plot was set up for field research and separated into 5 × 5 m areas with markers at their centres (Figure 1). Eight of the 25 points, represented on the sample plot scheme in green colour, were randomly selected as representatives and were continuously measured afterward.

Field visits were conducted from May to October in the 2014–2017 period every 14 days in the mornings at 9:00 – 12:00 hours and for each of the 8 points three technical replicates were taken. Soil respiration and soil temperature were measured using an ADC BioScientific Ltd. LCpro+ instrument, while soil humidity was determined using Kopecky cylinders (Kopecký, 1909). At the same time, air temperature and humidity at 30 cm and 200 cm above the ground was measured. In 2016, measurements were not taken between June and September due to damage to the sample plot and a malfunction of the instrument.

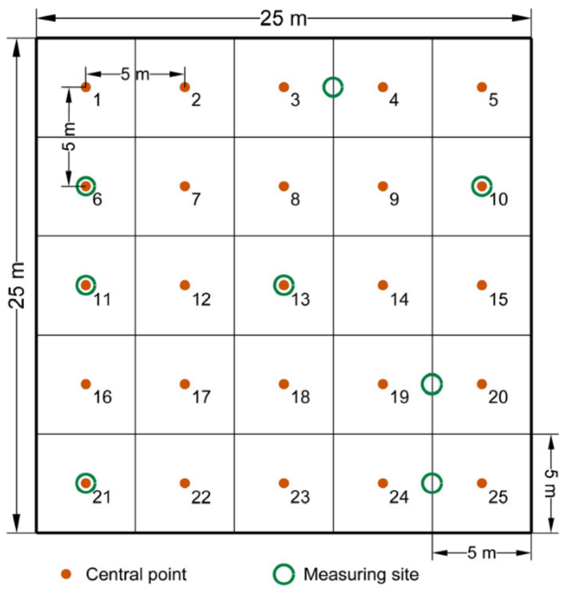

Figure 1. Sample plot scheme.

2.3. Data Analysis

The statistical methodology employed in this study aimed to explore the temporal variation in soil respiration across multiple sampling dates while accounting for nested data structures and overdispersion commonly observed in count data. The measurement data were processed using the R Studio software, version 2024.12.0+467. The data were analysed using generalized linear mixed models (GLMMs), an approach well-suited for hierarchical datasets where observations are clustered within random effects, such as replicates and samples in our study. A Poisson model was constructed under the assumption of equidispersion, where the mean and variance of the response variable are equal. To account for potential overdispersion, a negative binomial model was also fitted, which introduces an additional dispersion parameter, allowing the variance to exceed the mean. Both models included fixed effects for sampling date and replicate, alongside a random intercept for the sample variable to capture unobserved heterogeneity at the sample level.

3. Results

A total of 32 field visits were conducted between 2014 and 2017 to measure site-specific air temperature and humidity at 30 cm and 200 cm, and soil temperature and humidity. A deviation from the standard approach occurred in 2016, when no measurements were conducted during the period between June and September.

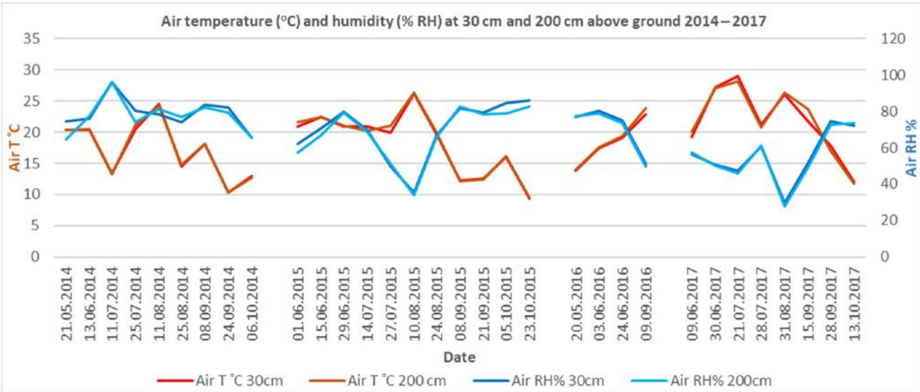

Figure 2. Air temperature (°C) and humidity (% RH) at 30 cm and 200 cm above ground 2014–2017.

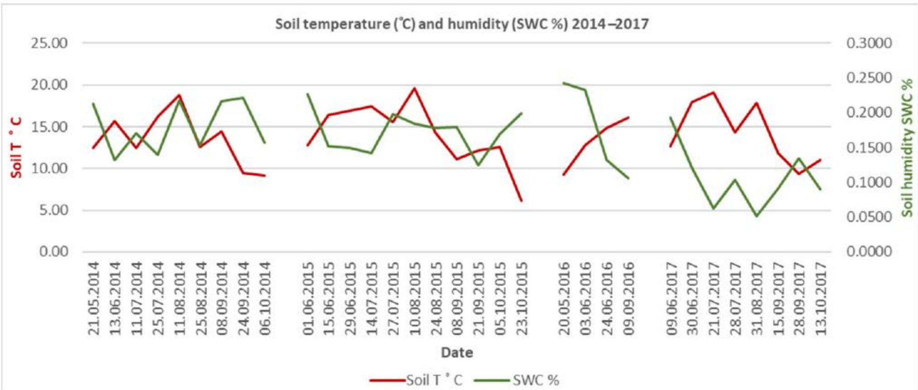

Figure 3. Soil temperature (°C) and humidity (% SWC) 2014–2017

The analysis of the site-gathered data for air temperature (°C) and humidity (% RH) at 30 cm and 200 cm above ground (Figure 2) and soil temperature (°C) and humidity (% SWC) at 20 cm below ground (Figure 3) have shown proportional correlation. April and May have the highest air humidity, followed by the hot and dry June–September period. Soil humidity and soil temperature are strongly correlated. The trend of average soil respiration values during the research period is presented in Figure 4.

During 2014, the values of soil respiration ranged from 0.05 μmol CO_2 m^{-2} s^{-1} on September 8, 2014, at site 21, to 6.92 μmol CO_2 m^{-2} s^{-1} on July 25, 2014, at site 13. In 2015, soil respiration values ranged from 0.02 μmol CO_2 m^{-2} s^{-1} on August 24, 2015, at site 6, to 7.93 μmol CO_2 m^{-2} s^{-1} on September 21, 2015, at site 13. In 2016, soil respiration values ranged from 0.29 μmol CO_2 m^{-2} s^{-1} on May 20, 2016, at site 13, to 4.14 μmol CO_2 m^{-2} s^{-1} on June 3, 2016, at site 6. In 2017, the measured values of soil respiration ranged from 0.09 μmol CO_2 m^{-2} s^{-1} on August 31, 2017, at site 10, to 3.54 μmol CO_2 m^{-2} s^{-1} on July 21, 2017, at site 24/25.

The temporal pattern clearly shows a distinct seasonal trend, with higher soil respiration during the warmer period (June–August) and lower respiration during the cooler months (April–May and September–October), a seasonal pattern consistently observed across all four years of the study.

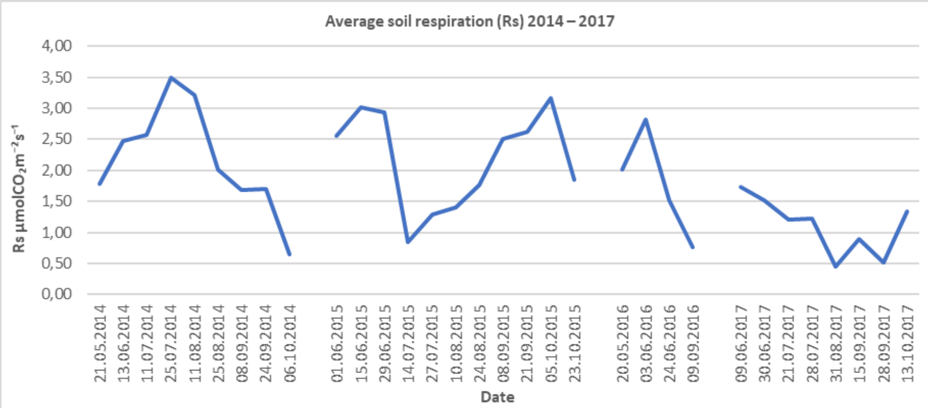

Figure 4. Trend of average soil respiration 2014 – 2017.

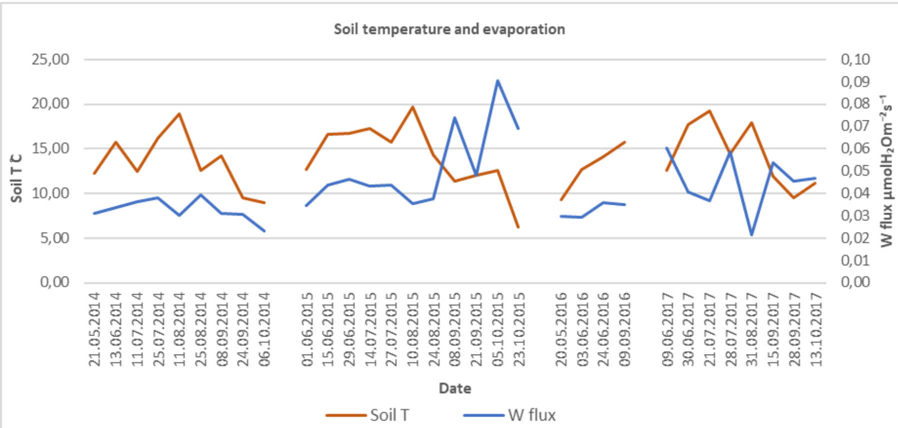

Figure 5. Relation of soil temperature and evaporation 2014 – 2017.

From Figure 5, a directly proportional relationship between soil temperature and evaporation can be observed - as soil temperature increases, evaporation also increases.

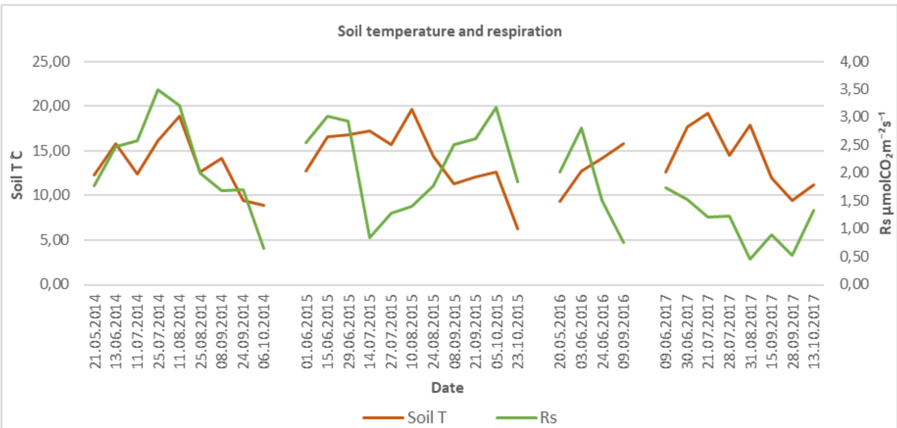

Figure 6. Relation of soil temperature and respiration 2014 – 2017.

The data analysis presented in Figure 6 indicates an inversely proportional relationship between soil temperature and soil respiration - as soil temperature increases, soil respiration decreases.

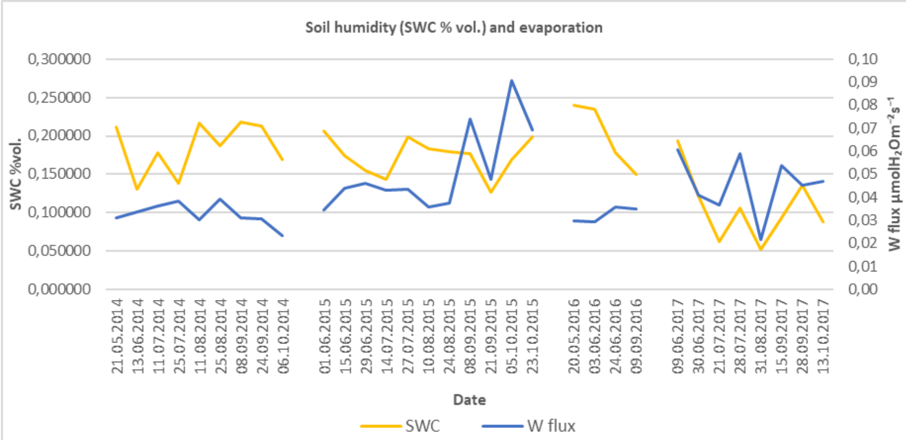

Figure 7. Relation of soil humidity and evaporation 2014 – 2017.

According to Figure 7, soil moisture and evaporation exhibit an inversely proportional relationship – as soil moisture increases, evaporation decreases.

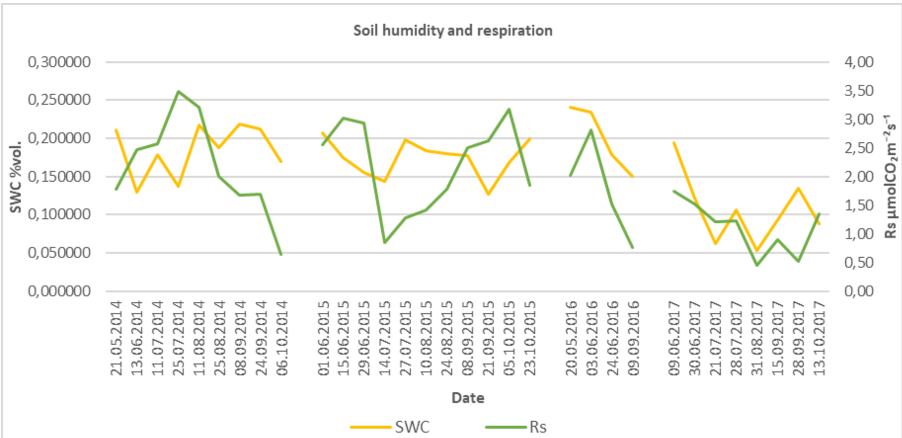

Figure 8. Relation of soil humidity and respiration 2014 – 2017.

The data analysis presented in Figure 8 indicates an inversely proportional relationship between soil moisture and soil respiration – as soil moisture increases, soil respiration decreases.

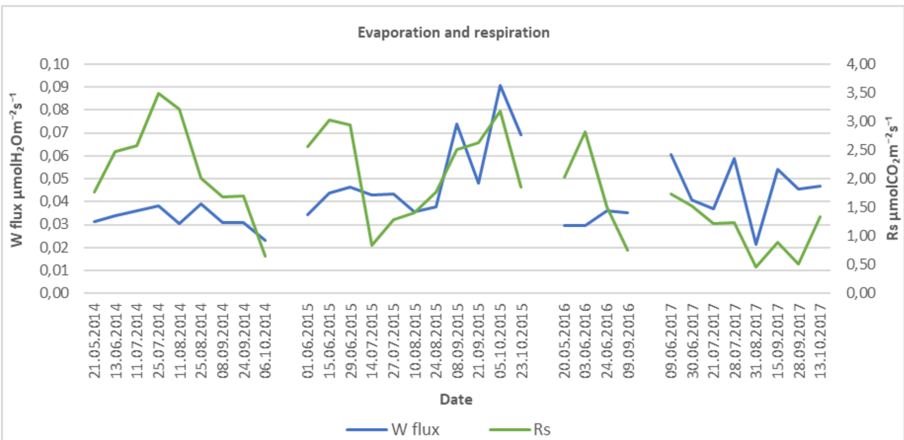

Figure 9. Relation of soil evaporation and respiration 2014 – 2017.

From Figure 9, it can be concluded that there is a directly proportional relationship between evaporation and soil respiration – as evaporation increases, soil respiration also increases. Figure 10 shows a visual representation of the correlation of biotic and abiotic variables with soil respiration.

In 2014, soil respiration (Rs) showed a significant very strong positive correlation with soil temperature (0.83), strong positive correlation with evaporation (0.65) and air temperature at 30 cm (0.61) and 200 cm (0.64), moderate positive correlation with air humidity at 30 cm (0.45) and 200 cm (0.41). Soil evaporation exhibited a moderate positive correlation with soil temperature (0.37) and with air humidity at 30 cm (0.48) and 200 cm (0.41). Soil moisture showed a moderate negative correlation with evaporation (–0.31) and soil respiration (–0.28). Soil temperature had very strong positive correlation with soil respiration (0.83), air temperature at 30 cm (0.89) and 200 cm (0.89), and moderate positive correlation with evaporation (0.37). No significant correlation was found between air temperature and air humidity; however, very strong correlations were observed between air temperature at 30 cm and 200 cm (1.0) and between air humidity at 30 cm and 200 cm (0.88).

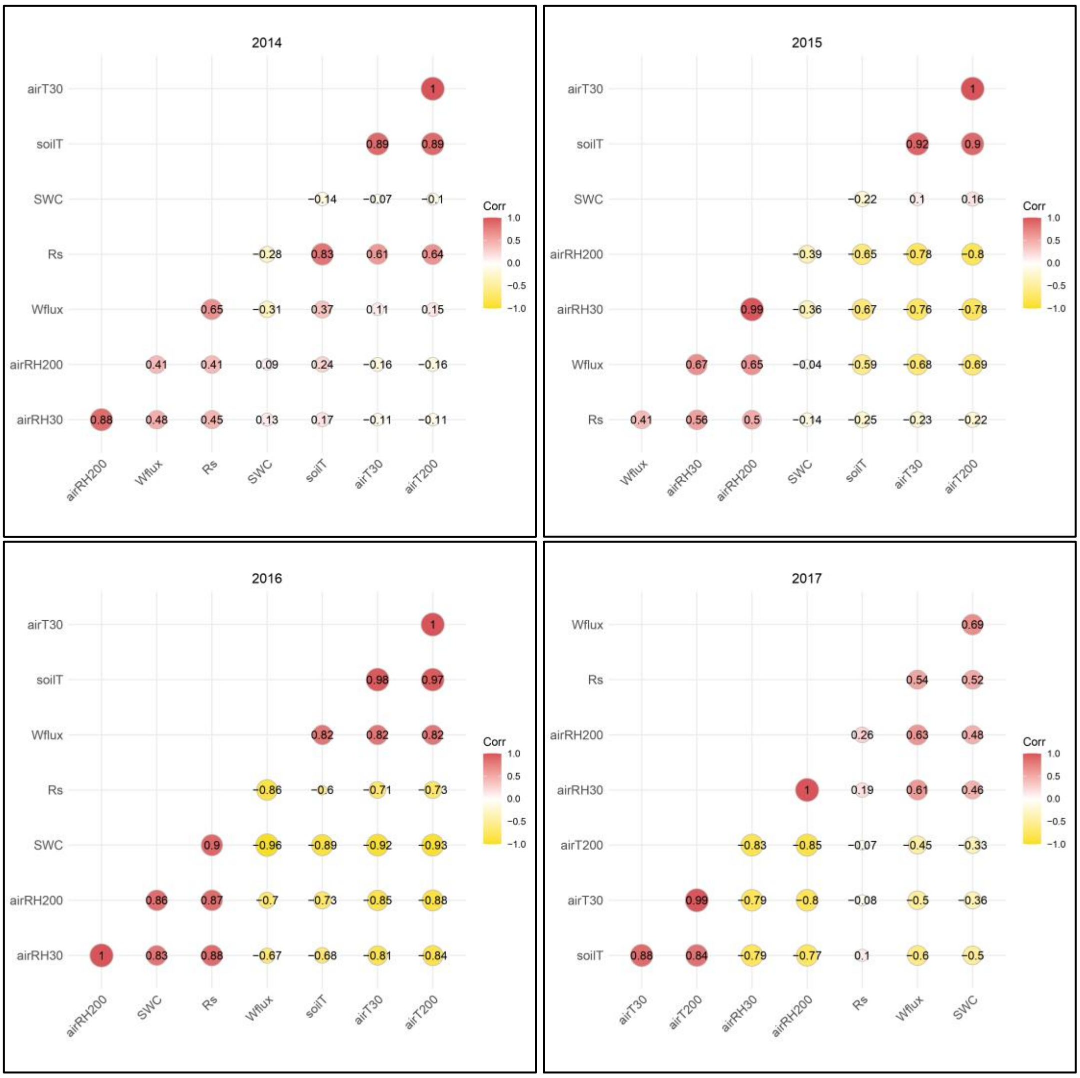

Figure 10. Correlation coefficients of all variables with soil respiration in:
(a) 2014, (b) 2015, (c) 2016 and (d) 2017.

In 2015, soil respiration (Rs) showed a moderate positive correlation with evaporation (0.41) and strong positive correlation with air humidity at 30 cm (0.56) and 200 cm (0.50). Soil evaporation exhibited a strong positive correlation with air humidity at 30 cm (0.67) and 200 cm (0.65), and moderate positive correlation with soil respiration (0.41), as well as a strong negative correlation with soil temperature (–0.59) and with air temperature at 30 cm (–0.68) and 200 cm (–0.69). Soil moisture showed a moderate negative correlation with air humidity at 30 cm (–0.36) and 200 cm (–0.39). Soil temperature showed strong negative correlation with evaporation (–0.59) and with air humidity at 30 cm (–0.67) and 200 cm (–0.65), as well as a very strong positive correlation with air temperature at 30 cm (0.92) and 200 cm (0.90). Air temperature at 30 cm and 200 cm showed a very strong correlation (1.0). The significant negative correlations reflect the relationships among ecological factors. Air humidity at 30 cm showed strong negative correlation with air temperature at 30 cm (–0.76) and 200 cm (–0.78), while air humidity at 200 cm had strong negative correlation with air temperature at 30 cm (–0.78) and 200 cm (–0.80).

In 2016, soil respiration (Rs) showed very strong positive correlation with soil moisture (0.90) and air humidity at 30 cm (0.83) and 200 cm (0.86), as well as a very strong negative correlation with evaporation (–0.86), and strong negative correlation with soil temperature (–0.60), and air temperature at 30 cm (–0.71) and 200 cm (–0.73). Soil evaporation showed very strong positive correlation with soil and air temperature at 30 cm (0.82) and 200 cm (0.82), but also very strong negative correlation with soil respiration (–0.86), soil moisture (–0.96), and strong negative correlation with air humidity at 30 cm (–0.67) and 200 cm (–0.70). Soil moisture showed a very strong positive correlation with soil respiration (0.90) and air humidity at 30 cm (0.83) and 200 cm (0.86), as well as very strong negative correlation with evaporation (–0.96), soil temperature (–0.89), and air temperature at 30 cm (–0.92) and 200 cm (–0.93). Soil temperature showed very strong positive correlation with evaporation (0.82) and with air temperature at 30 cm (0.98) and 200 cm (0.97), along with very strong negative correlation with soil moisture (–0.89) and strong negative correlation with soil respiration (–0.60) and air humidity at 30 cm (–0.68) and 200 cm (–0.73). Very strong positive correlation coefficient of 1.0 was found between air temperature at 30 cm and 200 cm, as well as between air humidity at 30 cm and 200 cm. Furthermore, air humidity at 30 cm showed very strong negative correlation with air temperature at 30 cm (–0.81) and 200 cm (–0.83), while air humidity at 200 cm showed very strong negative correlation with air temperature at 30 cm (–0.85) and 200 cm (–0.88).

In 2017, soil respiration (Rs) showed strong positive correlation with evaporation (0.54), soil moisture (0.52), weak positive correlation with air humidity at 30 cm (0.19) and moderate positive correlation with air humidity at 200 cm (0.26). Soil evaporation showed strong positive correlation with soil respiration (0.54), soil moisture (0.69), and air humidity at 30 cm (0.61) and 200 cm (0.63), as well as strong negative correlation with soil temperature (–0.60) and moderate negative correlation with air temperature at 30 cm (–0.50) and 200 cm (–0.45). Soil moisture showed strong positive correlation with soil respiration (0.52) and evaporation (0.69), and moderate positive correlation with air humidity at 30 cm (0.46) and 200 cm (0.48), as well as moderate negative correlation with soil temperature (–0.50) and air temperature at 30 cm (–0.36) and 200 cm (–0.33). Soil temperature showed very strong positive correlation with air temperature at 30 cm (0.88) and 200 cm (0.84), and strong negative correlation with evaporation (–0.60), soil moisture (–0.50), and air humidity at 30 cm (–0.79) and 200 cm (–0.77). Air temperature at 30 cm and 200 cm showed very strong correlation (0.99), as did air humidity at 30 cm and 200 cm (1.0). Air humidity at 30 cm showed strong negative correlation with soil temperature (–0.79) and air temperature at 30 cm (–0.79), and strong negative correlation with air temperature at 200 cm (–0.83), while air humidity at 200 cm showed strong negative correlation with soil temperature (–0.77) and very strong negative correlation with air temperature at 30 cm (–0.80) and 200 cm (–0.85).

Overall, the results demonstrate strong seasonal dynamics and interannual variability in soil respiration influenced by abiotic conditions.

4. Discussion

Soil respiration (Rs) represents a key component of the Earth system puzzle. To understand how the Earth system functions, it is essential to comprehend the role that soil respiration plays in regulating atmospheric CO_2 concentrations and climate dynamics (Yiqi and Xuhui, 2006). It is expected that global warming will stimulate soil respiration, thereby reducing the total carbon content in the planet's ecosystems (Raich and Schlesinger, 1992).

The correlation analyses for the four-year period (2014–2017) revealed that soil respiration (Rs) is primarily controlled by soil temperature, soil moisture, and evaporation, with the strength and direction of these relationships varying between years.

In 2014, Rs showed strong positive correlations with soil and air temperature, confirming that temperature is a dominant driver of soil respiration under favourable moisture conditions. In 2015, the relationships became more complex: Rs correlated positively with evaporation and air humidity but negatively with temperature, suggesting possible thermal stress or reduced microbial efficiency at higher temperatures. The year 2016 exhibited a reversed pattern, with Rs showing strong positive correlations with soil moisture, but negative correlations with temperature and evaporation. This indicates that water availability was a limiting factor for respiration in that period. In 2017, Rs maintained moderate positive correlations with evaporation and soil moisture, again emphasizing the interactive role of temperature and moisture in regulating soil CO_2 efflux.

Overall, the results demonstrate that soil respiration does not respond linearly to temperature or moisture alone, but rather to the combined and sometimes opposing effects of these variables. The observations of soil carbon fluxes throughout the 2014–2017 study period indicate that increasing air and soil temperatures and soil water availability have a major impact on them. These findings support previous reports that global warming may stimulate soil respiration while reducing total ecosystem carbon stocks (Berger et al. 2010), and they underscore the importance of soil biophysical processes in forest carbon dynamics.

Future studies should include continuous year-round measurements and incorporate biotic variables, such as root biomass or microbial community structure, to improve research accuracy.

5. Conclusions

In summary, the extensive analysis conducted over the four-year period from 2014 to 2017 has revealed intricate relationships between abiotic (climate) factors and soil respiration intensity. The key findings indicate that these factors, particularly variations in air temperature and humidity, significantly impact soil respiration.

Considering the results from all analysed years, it can be concluded that soil respiration is significantly related to soil temperature and moisture, although these relationships are not consistent across seasons. In most cases, soil respiration positively correlates with soil temperature; however, in some years, a nonlinear response has been observed, which may indicate thermal stress at higher temperatures. Similarly, in relation to soil humidity, soil respiration exhibits a peak point after which it declines, supporting the concept of an optimal moisture level for enzymatic activity and soil respiration.

These results highlight the importance of monitoring soil respiration under changing climate conditions and provide baseline data for assessing carbon fluxes in temperate forest ecosystems.

References

1. Berger, T.W. Inselsbacher, E., Zechmeister-Boltenstern, S. (2010): Carbon dioxide emissions of soils under pure and mixed stands of beech and spruce, affected by decomposing foliage litter mixtures. Soil Biology and Biochemistry 42: 986–997.
2. Bošnjak, Đ., Dragović, S., Hadžić, V., Babović, V., Kostić, N., Burlica, Č., Đorović, M., Pejković, M., Mihajlović, T.D., Stojanović, S., Vasić, G., Stričević, R., Gajić, B., Popović, V., Šekularac, G. Nešić, Lj., Belić, M., Đorđević, A., Pejić, B., Maksimović, I., Karagić, Đ., Lalić, B., Arsenić, I., (1997): Metode istraživanja i određivanja fizičkih svojstava zemljišta. In: Bošnjak, Đ. (Eds.), Komisija za fiziku zemljišta, Jugoslovensko društvo za proučavanje zemljišta, Novi Sad, pp. 1–278.

3. Buscot, F. (2005): What are soils? In: Varma A. Buscot F. (eds) Microorganisms in soils: roles in genesis and functions. Soil Biology, vol 3. Springer, Berlin, Heidelberg.
4. Cencelj, J. (1966): Određivanje reakcije zemljišta. Priručnik za ispitivanje zemljišta, Knjiga I, Jugoslovensko Društvo za proučavanje zemljišta, Beograd.
5. Govedarica, M. Jarak, M. (1995): Soil microbiology. University of Novi Sad, Faculty of Agriculture, Institute of Field and Vegetable Crops. Novi Sad, Serbia. 1–112.
6. Janković, M., Stefanović, K. (1969): Basic characteristics and dynamics of soil respiration in some forest biocoenoses on Fruška Gora. Acta Botanica Croatica 28: 171–190.
7. Kastori, R.I., Kádár, P., Sekulić, D., Bogdanović, N., Milošević, M., Pucarević (2006): Uzorkovanje zemljišta i biljaka nezagađenih i zagađenih staništa. Biljni lekar 34(2): 178–179.
8. Kopecký J. (1909): Abhandlung über die agronomisch-pedologische Durchforschung eines Teiles des Bezirkes Welwarn. Prag, Verlag des Landesculturrathes für das Königreich Böhmen.
9. Lloyd, J., Farquhar, G.D. (1996): The CO_2 dependence of photosynthesis, plant growth responses to elevated atmospheric CO_2 concentrations and their interaction with soil nutrient status. I. General Principles and Forest Ecosystems. Functional Ecology 10(1): 4–32.
10. Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D. (2011): A Large and persistent carbon sink in the world's forests. Science 333(6045): 988-993.
11. Pilipović, A., Orlović, S., Galić, Z., Stojnić, S., Borišev, M., Nikolić, N. (2011): Rezultati monitoringa disanja zemljišta dve različite bukove zajednice u toku vegetacionog perioda. Topola 187/188: 65–75.
12. Racz, Z. (1971): Određivanje mehaničkog (teksturnog, granulometrijskog) sastava zemljišta. *Priručnik za ispitivanje zemljišta*, Knjiga V, Jugoslovensko Društvo za proučavanje zemljišta, Beograd.
13. Raich, J.W., Schlesinger, W.H. (1992): The global carbon-dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus Series B - Chemical and Physical Meteorology 44: 81–99.
14. Stefanović, K. (1985): Ekološka studija produkcije ugljendioksida u nekim listopadnim šumama Fruške Gore. Glasnik Instituta za botaniku i botaničke bašte Univerziteta u Beogradu 19: 191-231.
15. Yiqi, L., Xuhui, Z. (2006): Soil respiration and the environment. Academic Press.