https://doi.org/10.17221/110/2022-PSE

CO_2 emissions in a soil under different tillage practices

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Citation: Mühlbachová G., Kusá H., Růžek P., Vavera R. (2022): CO_2 emissions in a soil under different tillage practices. Plant Soil Environ., 68: 253–261.

Abstract: CO_2 emissions represent one of the greenhouse gases significantly affecting climate change. Reduced tillage practices can contribute to the mitigation of CO_2 emissions from soils. The effect of tillage practices with different straw incorporation on CO_2 emissions was studied in field experiments in the years 2020 and 2021. The winter wheat straw was used in 2020, and spring barley straw in 2021. Treatments were: (1) chiselling to 10–12 cm; (2) shallow chiselling (5–6 cm depth); (3) straw mulch, and (4) stubble. The chiselling to 10–12 cm in the warm summer period of 2020 increased the CO_2 emissions from soils even twice in comparison with other used soil tillage practices. The soil temperature and CO_2 emissions decreased in the following order: chiselling to 10–12 cm < shallow chiselling ≤ stubble ≤ mulch in 2020. Low CO_2 emissions without significant differences among treatments were observed in the year 2021 when low soil temperatures and excessive soil water content filling soil pores caused by intensive precipitations (23 mm) coming shortly after soil tillage were observed. The CO_2 emissions from soils are affected by a number of factors. Among them the current weather conditions as well as soil temperature the depth of soil tillage and handling of postharvest residues, are important.

Keywords: stubble treatment; soil disturbance; carbon dioxide; soil humidity and temperature; crop debris

The ongoing weather changes, more frequent periods of drought, irregular precipitations and increasing temperatures bring new challenges regarding soil tillage systems which, if correctly used, should mitigate the losses of the soil organic matter and maintain acceptable crop yields. Agricultural carbon and water budgets are affected by crop species, stubble management practices, amount of stubble residues, climatic and soil conditions. In the context of climate change, it is critical to investigate the long-term effects of these environmental drivers and farming activities on carbon and water dynamics (Chi et al. 2017).

The soil properties are altered with a change of the soil tillage depth (Hussain et al. 1999), current weather conditions which affect CO_2 fluxes through effects on soil water and temperature regime (Feiziene et al. 2012) and also with cropping systems and nitrogen fertilisation (Sainju et al. 2008). Traditional tillage techniques such as ploughing to 25–30 cm or disc harrowing to 15–20 cm promote loss of the soil organic matter (SOM) due to significant amount of CO_2 emissions to the atmosphere and leads to subsequent problems as a disruption of soil aggregates or increased soil erosion (Melero et al. 2009).

The use of crop residues as mulching materials or organic fertiliser can help to improve the soil organic carbon (SOC) and crop grain yield (Wang et al. 2019). Nishigaki et al. (2021) showed that the carbon storage after crop residue incorporation is not significant in a short time view but it increases with time. This is in accordance with Lu et al. (2015) who found a significant increase in soil organic matter after 10 years of straw incorporation in the soil whereas the short-term effect was not significant.

The CO_2 emissions from soil are an important part of the carbon cycle in terrestrial ecosystems and tillage practices can affect drivers of CO_2 production and therefore influence CO_2 emissions by soils (Dong et al. 2017).

Improved management practices can rebuild carbon (C) stocks in agricultural soils and help to mitigate

Supported by the Ministry of Agriculture of the Czech Republic, Project No. MZE-RO0418.

https://doi.org/10.17221/110/2022-PSE

CO_2 emissions (Paustian et al. 2000). The CO_2 emissions from the soil also depend on various factors such as soil temperature and soil moisture content, or an interaction between these two, and the availability of substrates (Lu et al. 2015, Dong et al. 2017). Soil CO_2 emissions increase with the increasing of soil temperature and depend also on seasonal soil temperature variation (Wang et al. 2019). The deficiency of precipitations affects negatively the gradual post-harvest residue decomposition (Lopez-Sangil et al. 2018) serving as an important source of organic compounds entering a soil. The tillage practice (i.e. straw incorporation or mulching) represents an important factor in the decomposition process, as it affects the water regime within the soil and the contact area of residues and soil Nishigaki et al. (2021).

Straw mulch can under specific conditions such as the amount and quality of soil aggregates and nitrogen fertilisation stimulate soil microbial activity and increase CO_2 emissions to the atmosphere (Zaman et al. 2002, Lenka and Lal 2013). The long-term application of crop residues also increases the content of small macroaggregates (> 250 µm) in the surface soil layer, which then leads to the accumulation of high carbon and nitrogen concentrations, which in turn serve as a substrate for microbial growth and subsequent CO_2 emissions (Lenka and Lal 2013). On the other hand, Curtin et al. (1998, 2000) showed that the straw remaining on the soil surface decreased about 5 times CO_2 emissions in comparison with straw incorporation under conventional tillage. In addition, Nishigaki et al. (2021) found a decrease in CO_2 emissions after mulching straw residues. The mineralisation of soil organic matter depends on temperature, precipitations, the chemical composition of crop residues, the structure and composition of microbial communities, and the C: N ratio in the soil after the incorporation of straw (Grzyb et al. 2020).

Soil tillage in summer is carried out before sowing of crops needing early sowing (i.e. oilseed rape). The temperatures exceeding 20–25 °C on a daily average and 30 °C in the afternoon are often measured in the summer period and favour higher CO_2 emissions. In this case, the use of mulch residues left on the soil surface can positively affect various aspects of the cropping system such as the increase of water infiltration due to the decrease of runoff, reduction of soil erosion, increase in moisture retention, weed control and reduction of soil temperature in summer (Campiglia et al. 2014, Mancinelli et al. 2015).

The aim of the research was therefore to evaluate the effects of different soil tillage practices carried out after cereal harvest on soil temperature, humidity and CO_2 emissions from soil.

MATERIAL AND METHODS

Field experiments. The field experiments studying CO_2 emissions under different soil tillage treatments were carried out in the Crop Research Institute at Prague – Ruzyně, Czech Republic (50.0891708 N, 14.2964372 E, altitude – 340 m a.s.l.; soil type – Illimerized Luvisol, C_{org} – 1.25%). The thirty years annual average precipitation was 513 mm, and the annual mean air temperature was 9.0 °C. Experiments were conducted under natural weather conditions from August to September after the winter wheat (2020) and spring barley (2021) harvest.

At the beginning of the experiments, the strips (50 × 6 m) for each tillage technology were created. The middle part of each strip of length 25 m was chosen for measurements. Tillage technologies were the following: the chiselling (depth 10–12 cm), shallow chiselling of soil (5–6 cm), untreated soil with mulching of the grounded straw on the surface and untreated soil with stubble and straw cover. Soil tillage or mulching was carried out 7. 8. 2020 and 30. 7. 2021, respectively. The straw yield of winter wheat was 7.5 t/ha in 2020 and that of spring barley straw was 6.1 t/ha in 2021. All harvested straw was used in the experiment according to the tillage technology. The ratio of surface cover with straw of both crops was on average 10–15% for chiselling to 10–12 cm, 30–40% for shallow chiselling, 80–90% for stubble and 90–100% for mulch.

Temperature. The daily air temperatures and precipitations were measured by means of the meteorological station of Crop Research Institute. The soil temperatures were measured in three repetitions by means of Tinytag Talk 2 Data Loggers (Chichester, UK) in 5 cm depth. The daily medium values were calculated from temperatures determined in 30 min intervals.

Soil moisture. The volumetric soil moisture was determined to 12 cm depth by means of FieldScout TDR Soil Moisture Meter (Spectrum Technologies, Bridgend, UK) on 10 places within each strip. The gravimetric soil moisture was measured in soils sampled in 0–20 cm depth by drying at 105 °C.

CO_2 emissions. The CO_2 emissions were measured in 3–7 days intervals. The CO_2 emissions were measured by means of LI-COR 8100 Automated Soil

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CO_2 Flux system (Lincoln, USA) equipped with 8150 Multiplexer and long-term chambers (LI-8100-104, Lincoln, USA) (diameter 20 cm) and operating in an open-closed system. Four CO_2 measurements were carried out during each measurement day for every treatment in regime 2:30 min closed chamber, the start of reading after 20 s, 45 s purchase time after opening and consecutive changing of treatments.

Statistical analysis. Statistical calculations were performed using Statistica 14.0 software (TIBCO, Palo Alto, USA). The results were expressed as mean values for each treatment and type of measurement. In the case of volumetric soil moisture, 10 measurements were taken into consideration. One-way ANOVA was used to evaluate the effects of treatments. The same letters in the figures indicate statistically identical values according to Tukey's test ($P < 0.05$). The statistical evaluation was performed for each sampling day separately.

RESULTS AND DISCUSSION

Air and soil temperature and moisture. The field experiment studying the CO_2 emissions in the year 2020 (from 7. 8. 2020 – soil chiselling and straw mulching to 7. 9. 2020) was characterised by air temperatures between 11.5–26.0 °C with an average of 20.8 °C. Total precipitations were 40.7 mm (Figure 1A). A week before the start of the experiment the precipitations reached in total 24.4 mm. The highest precipitations occurred at the beginning of the experimental period (20.5 and 12.6. mm before the second and third sampling, respectively) when the average temperatures reached 23.3 °C.

The field experiment in 2021 (from 6. 8. 2021 – soil chiselling and straw mulching, to 14. 9. 2021) was characterised by air temperatures between 13.0–23.7 °C with an average of 17.5 °C. Total precipitations during the study period reached 55.8 mm with greater intensity at the beginning of the experiment (33.6 mm) (Figure 1B). Higher precipitations were noted also one week before the start of the experiment reaching 36.8 mm. In comparison with the year 2020, the temperatures were lower on average at 3.3 °C and precipitations were higher at 15.1 mm. This weather at the end affected the soil temperatures and finally also the CO_2 emissions from soils.

Soil temperatures in 2020 are given in Figures 2A, B. Depending on soil treatment and straw management, the soil temperature was warming up intensively during a sunny day and getting cold at night. The soil temperature under chiselling to 10–12 cm showed the highest temperature oscillation during 24 h reaching up to 20 °C in comparison with the other treatments. Little straw cover (10–15%) in this treatment as well as greater air access could cause higher daily differences in soil temperature in comparison with other treatments. The shallow chiselling and non-treated soil with stubble or even covered by mulch did not warm up so much during the day and usually reached a maximum difference of about 10 °C. The highest afternoon temperatures of soil under chiselling to 10–12 cm were higher by 5, 6 or 8 °C than that under shallow chiselling, stubble or mulch, respectively (Figure 2A). The all-day average temperatures were the highest in soil under chiselling to 10–12 cm and decreased in order: chiselling >> shallow chiselling > stubble ≥ mulch (Figure 2B).

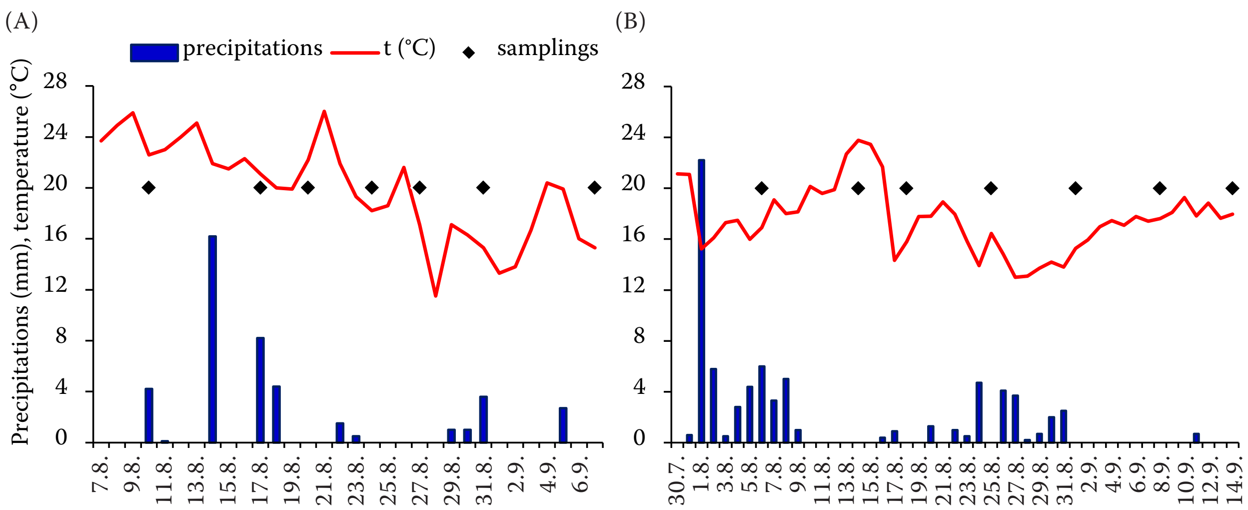

Figure 1. Precipitations and temperatures during CO_2 measurements under different soil tillage practices in (A) 2020 and (B) 2021

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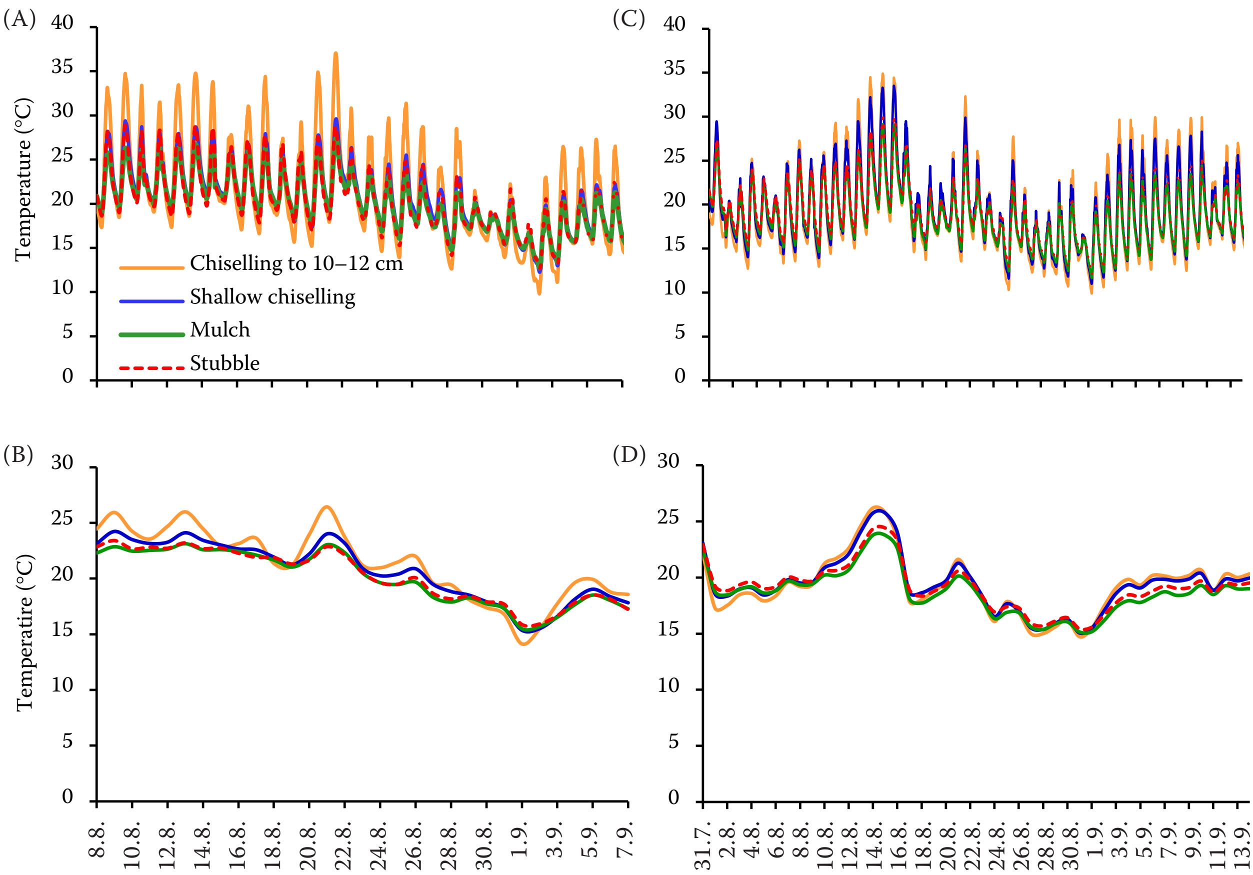

Figure 2. Soil temperature under different soil tillage practices: daily temperature oscillation (A) 2020 and (C) 2021; daily average (B) 2020 and (D) 2021

The soil temperatures in 2021 reached a maximum daily oscillation of temperature of about 17 °C under chiselling to 10–12 cm. The difference in daily temperature oscillation between chiselling to 10–12 cm and other tillage practices was not so big as in warmer weather observed in the previous experiment with winter wheat and depending on used tillage practice (shallow chiselling, mulch, stubble) reached a difference in soil temperatures about 2–3 °C (Figure 2C). In addition, daily soil temperatures in the year 2021 were lower in comparison with the year 2020 (Figure 2D).

Reducing the intensity of tillage or better soil at an undisturbed state and mulch cover significantly reduced soil warming, which is important for reducing water evaporation from soil and SOM mineralisation. Noor et al. (2021) showed that wheat mulch decreased daily soil temperatures by 1.9 °C and 1.5 °C on average in 0–15 cm and 15–30 cm soil layers, increased soil moisture and the end improved also yields of the following crop. The soil temperature decreased in the following order: chiselling to 10–12 cm << shallow chiselling < stubble ≤ mulch and reflected the straw cover 10–15% under chiselling to 10–12 cm, 30–40% under shallow chiselling, 80–90% under stubble and 90–100% under mulch.

The lowest moisture content in 2020 measured by both methods – volumetric (Figure 3A) and gravimetric one (Figure 3B) was found in the soil under chiselling to 10–12 cm. Volumetric humidity of soil under deep chiselling was significantly lower in comparison with other treatments. The soil moisture in experimental treatments increased in the following order: chiselling to 10–12 cm << stubble < shallow chiselling < mulch and reflected the straw cover 10–15% under chiselling to 10–12 cm, 80–90% under stubble, 30–40% under shallow chiselling, and 100% under mulch.

The different kinds of tillage in the year 2021 showed a significant difference in volumetric moisture only between chiselling to 10–12 cm and other tillage practices, which were not significant among themselves (Figure 3C). The gravimetric moisture mostly did not differ significantly in soils in 2021, however, the

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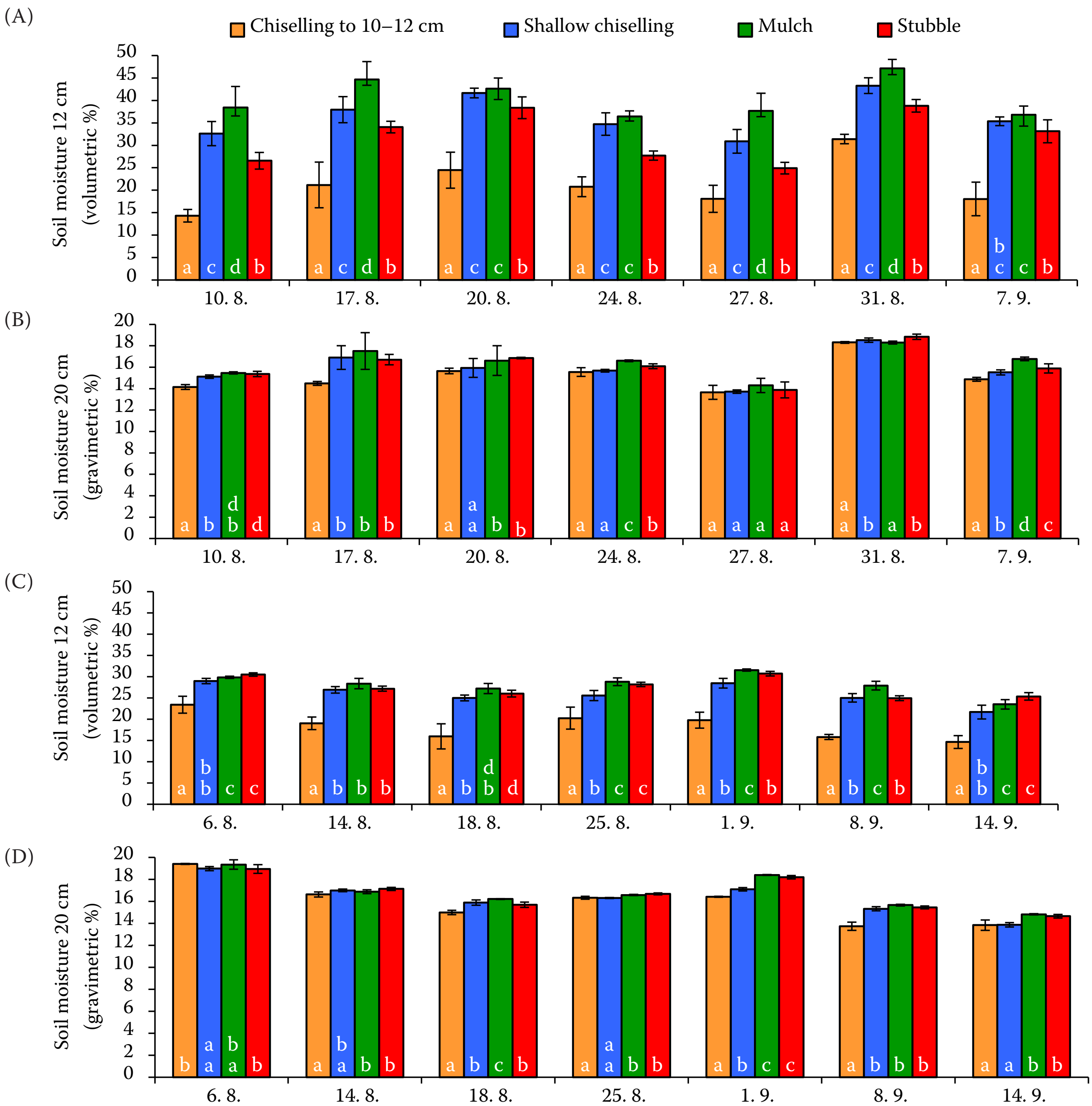

Figure 3. Soil moisture under different soil management: Winter wheat (A) volumetric moisture in 12 cm; (B) gravimetric moisture in 20 cm; spring barley (C) volumetric moisture in 12 cm, and (D) gravimetric moisture in 20 cm

chiselling to 10–12 cm tended to decrease the gravimetric moisture in the second half of the experiment (Figure 3D). Minor differences among treatments in both experimental years were found in moisture gravimetric in comparison with volumetric one, among other things owing to deeper studied layer always including a certain layer of uncultivated soil.

The obtained results showed the importance of soil cover which is able to maintain more soil moisture in comparison with chiselling to 10–12 cm leaving only about 10–15% of straw on the soil surface. The soil which is covered only partly as it was seen under shallow chiselling covering the soil with straw from about 30–40% was able to maintain twice soil moisture in comparison with chiselling to 10–12 cm. In the year 2020, the best moisture maintenance was observed under mulch which fully covered the soil. Similarly, Noor et al. (2021) found mulch to increase soil moisture measured gravimetrically in a soil layer of 0–15 cm of 2.5% under mulch in comparison with

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no-mulch treatment. Therefore, the mulch covering soil from 90–100% should be mainly in dry years recommended to maintain soil moisture.

CO_2 emissions. The soil temperature and humidity significantly affect the chemical and biological processes in the soil (Dong et al. 2017, Wang et al. 2019). In our experiments, the highest CO_2 emissions in 2020 were measured after chiselling to 10–12 cm differing significantly from other soil treatments among which there were no significant differences (Figure 4A). This finding suggests that the soil temperature was a major factor influencing CO_2 emissions. Similarly, Mancinelli et al. (2015) found that the summer period with the highest soil temperatures affected soil water content and CO_2 emissions and Guttières et al. (2021) reported that the rise of temperature from 15 °C to 20 °C increased basal soil organic matter mineralisation by 38% which contributed to higher CO_2 emissions. Our experiments showed that the postharvest residues on the soil surface covering the soil from 30–40% (Shallow chiselling); 80–90% (stubble) to 90–100% (mulch) decreased excessive soil warming and loss of the soil moisture (Figures 2 and 3) suggesting also lower organic matter mineralisation. Curtin et al. (1998) showed that the straw incorporation under conventional tillage and irrigation regime increased CO_2 emissions by about 5 times in comparison with the straw remaining on the soil surface. The other experiment by Curtin et al. (2000) showed that the straw remaining on the soil surface (3.6 t/ha) had also increased CO_2 fluxes, but the effect was small as compared with incorporated straw when from 4.6 t/ha remained on the soil surface only 1.4 t/ha. These results are in accordance with our field experiment carried out in 2020, in which the chiselling to 10–12 cm when only 15% of straw remained on the soil surface caused 7th and 20th August and 7th September 2020 twice as higher CO_2 emissions in comparison with other tillage practices with a higher percentage of soil cover with straw (30–100%) (Figure 3A). We did not achieve so high a difference in CO_2 emissions between chiselling to 10–12 cm and other tillage practices as Curtin et al. (1998) under irrigation regime, however, they can be comparable with Curtin et al. (2000) who noted CO_2 emissions about 20–25% lower under undisturbed soil compared to conventional tillage.

The results of a field experiment in 2021 conducted in colder and more rainy weather did not show practically any significant differences in CO_2 emissions among soil tillage practices (Figure 4B). These results probably reflect lower soil temperatures and daily

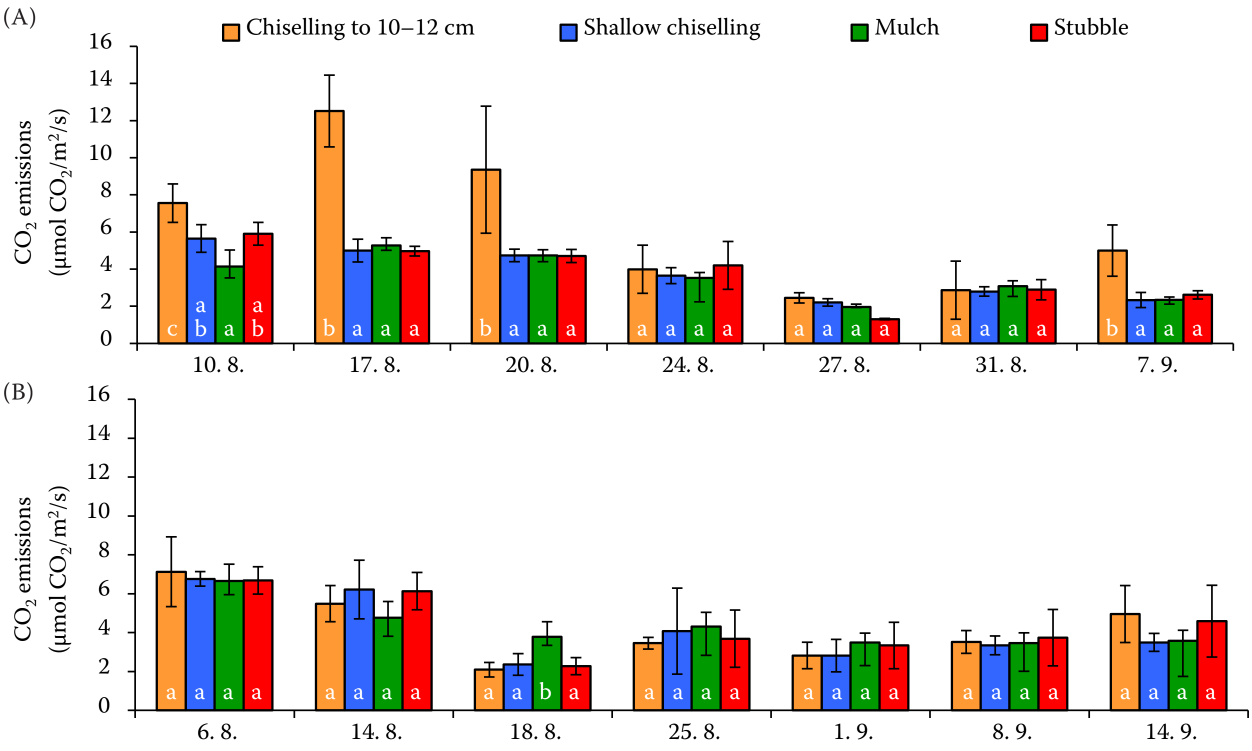

Figure 4. CO_2 emissions from soils under different soil tillage practices. (A) treatment after winter wheat harvest, and (B) treatment after spring barley harvest

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temperature oscillation during the experiment. In addition, the difference in soil temperatures was in the year 2021 only about 2–3 °C among treatments in comparison with the year 2020 when maximum differences reached 8 °C (Figure 2A, C).

Our results also showed that the straw left on the soil surface in a ratio of 80–100% (stubble and mulch) can be a good method to decrease CO_2 emissions from the soil at least during the warmer and drier summer period. Anyway, also shallow chiselling in 2020 covering only 30–40% with straw decreased significantly CO_2 emissions from soils in comparison with chiselling to 10–12 cm showing that a relatively low difference of about 5–6 cm in tillage can decrease significantly CO_2 emissions from soils. Curtin et al. (2000) suggest that lower CO_2 fluxes under no-tillage than under conventional ones were attributed to the slower decomposition of crop residues placed on the soil surface than when they were incorporated. In accordance with our results also Langeroodi et al. (2019) and Mancinelli et al. (2015) found the highest CO_2 emissions in August. Lower soil disturbance leads in summer to decreased soil temperature, maintenance of soil moisture and reduced CO_2 emissions. Langeroodi et al. (2019) also reported that CO_2 emissions were the lowest under no-tillage associated with wheat residue mulch. In addition, Guo et al. (2021) showed that no-tillage practice with mulch can successfully reduce CO_2 emissions from soil.

The soil moisture and temperature are generally related to the CO_2 emissions from soils (Dong et al. 2017). Wang et al. (2019) reported that CO_2 emissions raise with increasing soil temperature, which confirms our results in the experiment conducted in 2020. The highest CO_2 emissions were measured at the beginning of the observed period, shortly after soil tillage, i.e. after soil aeration. The highest CO_2 emissions under chiselling to 10–12 cm were found in 17. 8. and 20. 8. 2020 after rainfall on the dry warm soil surface (Figure 4A). In these days the measured values were even twice in comparison with other tillage treatments. A significant CO_2 emissions increase was observed also on 7. 9. 2020 due to previous precipitation and the warm weather at the beginning of September. On the above mentioned days, the difference among treatments was significant at $P < 0.05$ according to the Tukey test.

On the contrary, practically no significant differences in CO_2 emissions were found among tillage practices in the year 2021 (Figure 4B) showing the importance of precipitations, air and soil temperatures (Dong et al. 2017, Wang et al. 2019) on soil mineralisation processes. The low CO_2 emissions in 2021 found even under chiselling to 10–12 cm were probably caused by intensive precipitations (23 mm) coming shortly after soil tillage which could fill soil pores with water and decrease soil aeration and also lower soil temperature (Figure 2).

The postharvest residues remaining on the soil surface (mulch with crushed straw or stubble) were reduced in the warm summer season 2020 overheating of soil (Figure 2), and loss of soil moisture which resulted in lower CO_2 emissions from soils. The obtained data in 2020 resulted in significant correlations between CO_2 emissions and soil temperature (Figure 5) in different soil tillage practices whereas no significant differences were found in 2021 which both can confirm by Dong et al. (2017) and Wang et al. (2019) findings.

In conclusion, the field experiments with different straw incorporation management were carried out in the years 2020 and 2021. The results showed, that the depth of tillage, soil temperature and moisture is decisive for an increase in CO_2 emissions from soils. The chiselling to 10–12 cm early after cereal harvest in the warm summer period of 2020 increased the CO_2 emissions from soils even twice in comparison with other used soil tillage practices. CO_2 emissions in the year 2021 were lower in comparison with the year 2020 even under chiselling to 10–12 cm. The stubble with straw or straw mulching covering the soil surface from 90–100% during warm summer days and later straw incorporation in soil should be therefore preferred. The chiselling to 10–12 cm is often carried out in summer before sowing of the oilseed rape. According to our data, this manner can significantly increase CO_2 emissions from soils, mainly in warm weather when average daily temperatures exceed 20 °C. The soil tillage should be carried out later at lower temperatures as it can decrease CO_2 losses in comparison with tillage immediately after harvest in summer. Remaining stubble with straw or straw mulching which covers soil surface from 80% to 100% can be therefore good practice for mitigation of CO_2 emissions in the summer period (up to about 50%) in comparison with shallowing to 10–12 cm covered with straw by only about 10–15%. Higher straw cover up to 80–100% helps in summertime also to maintain the soil moisture after crop harvest and to prevent soil overheating.

Acknowledgement. We thank to Dana Hejnová for her valuable help with laboratory analysis.

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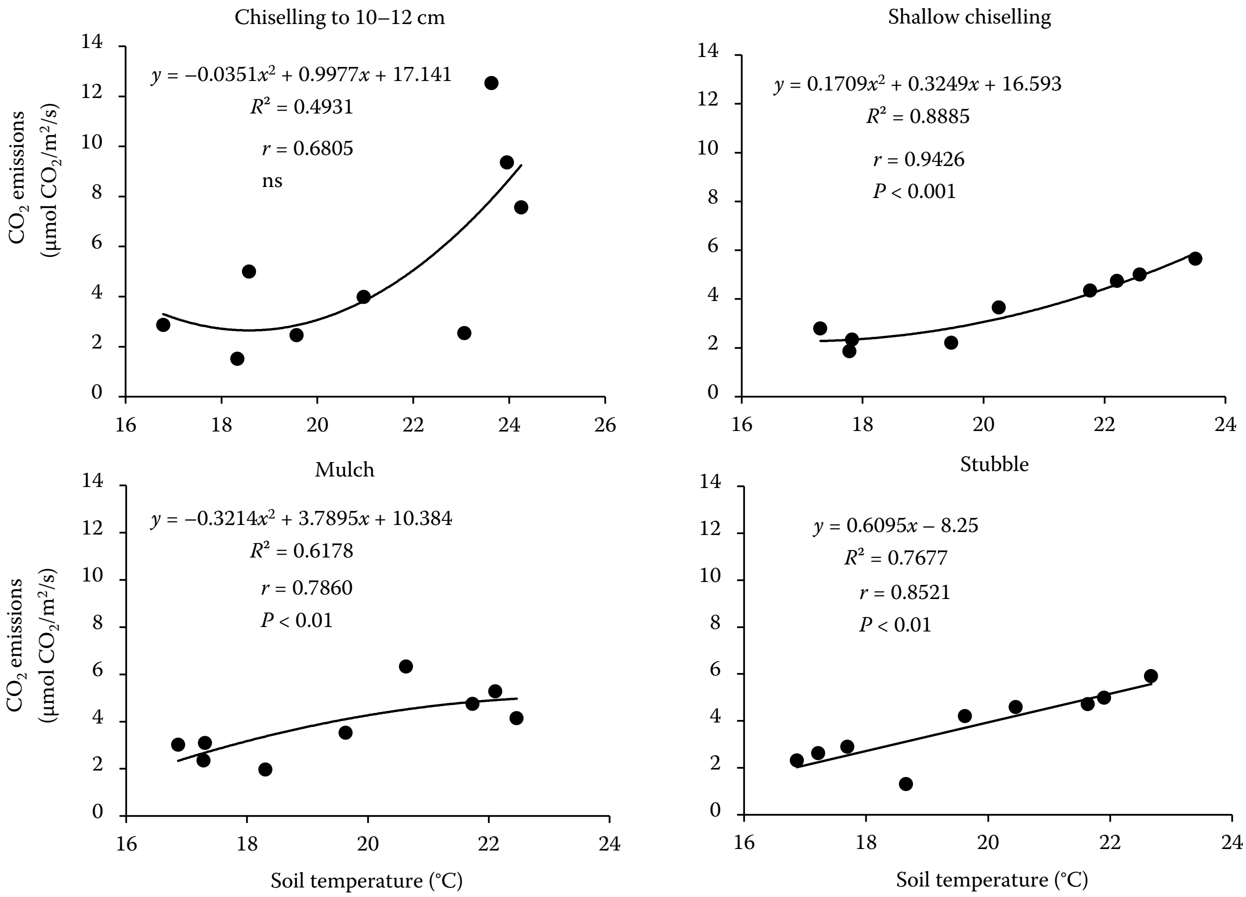

Figure 5. The relationship between soil temperature and CO_2 emissions from soil in 2020

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Received: May 30, 2022
Accepted: June 7, 2022
Published online: June 16, 2022