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The effect of slope gradient on the modelling of soil carbon dioxide emissions in different tillage systems at a farm using precision tillage technology in Hungary

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Abstract.

Understanding the role of natural drivers in greenhouse gas (GHG) emitted by agricultural soils is crucial because it contributes to selecting and adapting acceptable eco-friendly farming practices. Hence, Syngenta Ltd. collaborating with researchers, aimed to investigate the effect of two tillage treatments, conventional-tillage (CT) and minimum-tillage (MT) on soil carbon dioxide (CO_2) emissions. The research field is in Hungary. Soil columns were derived from different tillage systems to monitor the soil CO2 emissions under laboratory conditions. The soil penetration resistance was measured, and soil samples were also taken to determine total organic carbon (TOC). The moisture replenishment was performed equal to the degree of weekly theoretical evapotranspiration. The emissions of soil columns were measured every other day for five weeks, in 3 repetitions at room temperature. The data were evaluated by correlation analysis and a two-sample t-test at a significance level of $p<0.05$. The combined effect of soil and environmental factors on soil CO_2 emissions was investigated using stepwise multiple linear regression with a backward selection technique. The soil CO_2 emissions were significantly higher in the MT system compared to the CT system. Medium to strong negative correlations were found between the soil CO_2 emissions and relative humidity ($r=-0.68$ to -0.80), while the analysis showed a medium to a strong positive correlation between soil CO_2 emissions and moisture content ($r=0.63$ to 0.92). The analysis of the interaction of the observed factors and soil CO_2 emissions indicated significant differences at the different parts of the slope. At the bottom of the slope, the model based on TOC, air pressure and soil penetration resistance explained 85% of the fitted data. At the middle of the slope, the model including air temperature and pressure and TOC explained 99,8% of the fitted data. At the top of the slope, air temperature and pressure were the basis of the model that explained 75% the of fitted data. These observations highlighted the importance of monitoring different soil factors, which allows a site-specific approach for modelling soil CO_2 emissions in different parts of the field.

Keywords.

soil CO_2 emissions, Syngenta Ltd., different tillage systems, environmental factors, modelling

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Introduction

The reduction of greenhouse gas (GHG) emissions is one of the main challenges being faced in the areas of climate change. The 22% of total GHG emissions originated from the agriculture sector (Tubiello et al. 2013), but its share slightly but continuously decreased from 22% to 17% between 2008 and 2018 (FAO, 2020). Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities, thus contributing to warming the Earth. The cultivation of agricultural soils is one of the most important sources of carbon dioxide emissions after fossil fuel usage, industrial processes, and deforestation, which also facilitated the increase of CO_2 concentration in the atmosphere from 280 ppm to 416 ppm between 1750 and 2021 (Lal et al. 2007; Lovenduski et al. 2021).

According to Jobbágy and Jackson (2000), soils are the largest territorial source with storing 1 billion tons of the soil of organic carbon at a depth of 3 m of the topsoil. The application of conventional plough-based tillage systems contributes to carbon emissions by accelerating decomposition processes, thus reducing the organic matter content of the soil (Six et al. 2004). However, the extent of the decline is limited to 0-0,3 m soil depth according to Virto et al. 2012, while Ussiri and Lal (2009) found no difference between the organic matter content of till no-tilled soils when examining a depth of one meter.

The first research on the role of different tillage systems in CO_2 emissions has been available since the 1980s in the US (Lal et al. 1998a, 1998b) since 1999 in the European Union (Torres 1999) and from the 2000s. in Hungary (Jóri et al. 2004; Zsembeli et al. 2005; Kovács et al. 2008). The results are contradictory, and a no- or minimum-tillage farming system does not always result in better CO_2 emissions. Numerous studies have confirmed that the tillage farming system has higher carbon dioxide emissions than no-tillage and min-tillage systems (Reicosky 1997; Curtin et al. 2000; Ussiri and Lal 2009; Abdalla et al. 2016; Bilandžija et al. 2017). Examining full-year emissions, Ussiri and Lal (2009) observed that the tillage farming system emits 11.3 percent more carbon dioxide than the no-tillage farming system. Tillage and no-tillage soil management were examined by Alluvione et al. (2009), who observed a 14 percent increase in carbon dioxide emissions in conventionally cultivated areas. Al-Kaisi and Yin (2005) measured remarkably high, 58 percent higher carbon emissions in conventionally cultivated areas. The most recent research showed between 30 percent (Lu et al. 2015) and 40 percent (Alhassan et al. 2021) of excess carbon emissions from tilled agricultural land compared to cultivation that does not disturb the soil surface.

By contrast, researchers have found similar carbon dioxide emissions in tillage and no-tillage systems (Aslam et al. 2000; Li et al. 2010), while other studies have shown higher carbon dioxide emissions in areas cultivated without plough (Oorts et al. 2007; Kulmány et al. 2022). Oorts et al. (2007) found 13 percent higher carbon dioxide emissions in no-tillage systems. Cheng-Fang et al. (2012) examined carbon-dioxide emissions from tillage and no-tillage systems in central China, where 22–40 percent higher carbon dioxide emissions were found for no-till tillage. Kulmány et al. (2022) observed 5 and 25 percent higher carbon dioxide emissions from soil columns derived from the no-tillage farming system under controlled laboratory conditions, which changed periodically during the vegetation period. The increased carbon dioxide emissions measured in no-tillage areas are due to the higher water content of the soil surface and thus the resulting higher biological activity (Bilandžija et al. 2014). However, Dendooven et al. (2012) pointed out that plant residues on the surface of no-tilled soils may also contribute to higher carbon dioxide emissions. Jacinthe et al. (2002) found that plant residues increase carbon dioxide emissions from no-tilled soils by 26 percent compared to tilled soils.

The impact of the slope gradients on carbon content accumulation is a well-researched field in agriculture, but its role in CO_2 emissions has been only investigated since 2010. In Zimbabwe, it was found that *Odontotermes transvaalensis* termite mounds located in dambos (seasonal wetlands) were an essential source of GHGs, and emissions varied with catena position for CO_2 and methane (CH_4) (Nyamadzawo et al. 2012). Wang et al. (2017) investigated the impact of slope gradients and positions on CO_2 emissions in the semiarid Loess Plateau of China. They found that the CO_2 emissions were higher with 26.2% at the bottom slope than at the upper slope. The soil CO_2 emissions decreased exponentially with slope gradients observed by Hu et al. (2020), from 832.7 g m^{-2} yr^{-1} on the 0.5° slope to 380.9 g m^{-2} yr^{-1} when the slope gradient was 20°. Walkiewicz et al. (2021) found that the position in the forest gully had a significant effect on all soil variables with the gully bottom having the highest pH, C, N concentration, microbial biomass, catalase activity, and CO_2 emissions.

Further research is required to understand better the impact of slope gradients on soil CO_2 emissions in different tillage systems. Thus, the main aim of this research was (1) to monitor the CO_2 emissions of tilled and min-tilled soils in laboratory conditions, (2) to evaluate the impact of the environmental and soil factors on soil CO_2 emissions according to slope gradients and (3) to develop a general modelling approach to understand better the driving factor of CO_2 emissions in different slope positions.

Materials and methods

Location of research field

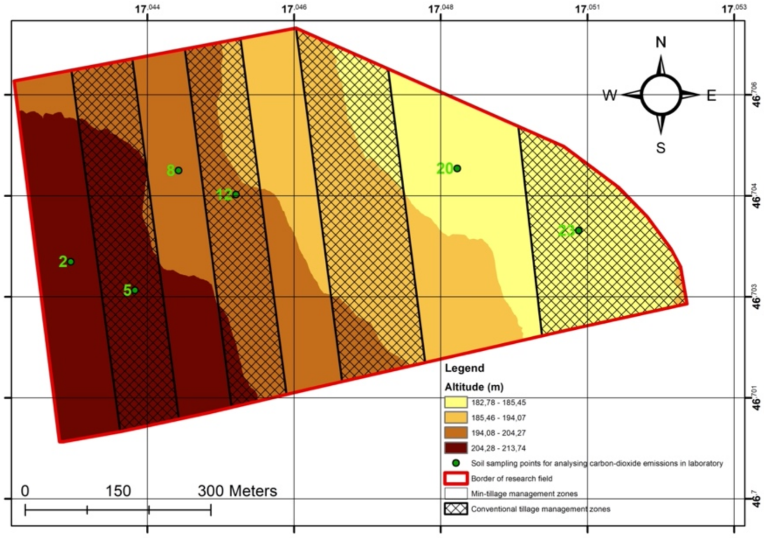


Figure 1. Location of research field.

The research was conducted in a field (40 ha) in Dióskál, Zala county, Hungary [N46°42'16.9" E17°02'50.4"]. The research field is a typical agricultural land on which a precision tillage system has been applied for 17 years. According to Csorba (2021), the climate of the region is characterized by a temperate climate with a mean annual temperature of 9.5-9.8 °C and 16.0-16,5°C in the growing season. According to literature data, the annual average rainfall is 600-650 mm, although the rainfall based on our observation was only 500-515 mm in 2021.

Maize (*Zea mays* L.) was grown in the research field in 2021 with a plant population of 72.000 per hectare with 142 kgN/ha, 146 kgP/ha and 88 kgK/ha fertilizer doze. Its previous crops were winter barley (*Hordeum vulgare L.*) in 2020 and winter coleseed (*Brassica napus L*) in 2019. The arable fields are characterized by eroded Luvisol with loam and clay texture, the parent material is loess (Soil Survey Staff, 2014). The field surface is heavily subjected to the soil erosion processes because the average slope gradient varies between 1-9 percent, in the West-East direction. The field is divided eight plots. Four plots are under the conventional tillage system (medium depth ploughing up to 27 cm and cultivating roller) and four management zones are under a conservation tillage (min-till) system (non-inversion tillage up to 25 cm and cultivating roller annually; deep chisel up to 45 cm every three years).

Soil sampling and laboratory analysis

At the beginning of the research, soil samplings were collected from 24 different points (3 samples from each management zones) from two different depths (0-15cm, 15-30cm). The chemical properties of samples were analyzed by a near-infrared sensor (Pinke et al. 2022). This procedure allowed the selection of the management zones where the carbon-dioxide emissions of soil sampling tubes have later been measured in laboratory conditions three times during the growing season. Soil samples from 0-15 cm were taken from 6 pre-defined points for analyzing the soil organic matter (*wet combustion, Turin method*) and total organic carbon content (M*SZ-08-0210-77*) in March, August, and October (Figure 1.).

Laboratory experiment and field measurements

The collection of soil tubes and their preparation, as well as laboratory experiments including the measurement of carbon dioxide (CO_2) emissions of soil tubes, weekly moisture replenishment (Dunay et al. 1968) and the determination of gravimetric water content of soil tubes (Black 1965) together with the measurement of soil penetration resistance (O'Sullivan 1991; NEN 5140,1996) were carried out according to Kulmány et al. (2022).

Statistical analyses

Microsoft Excel (2021) and its Data Analysis ToolPak were used to perform the statistical analysis. The soil heterogeneity was analyzed with descriptive statistics in the first step. To compare the rate of soil CO_2 emissions of two different tillage systems, a two-sample t-test was applied (Fischer 1925, Levene 1960). Pearson correlation analysis was performed to measure the strength of a linear relationship between the CO_2 emissions and other independent variables such as air temperature (AT), air pressure (AP), gravimetric water content (GWC), total organic carbon (TOC) and soil penetration resistance (PR). Multiple Linear Regression with Backward Elimination was used (Sellam and Poovammal 2016) to analyze the relationship between a single response variable (CO_2 emissions) with more controlled variables (independent variables). The multicollinearity between independent variables was tested (Kutner et al. 2004) with calculating the Variance Inflation Factor (VIF). To determine the accuracy of the forecast models, relative approximation error (RAE), root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE) were calculated (Niazian et al. 2018; Piekutowska et al. 2021).

Results

Variability of soil properties

The descriptive statistics show low ($CV \leq 15\%$) and medium ($CV \leq 30\%$) variability in all chemical properties regardless of tillage systems. High variability ($CV \geq 30\%$) was exclusively determined in soil penetration resistance of the topsoil (0-20cm), which refers to the application of different soil management. The minimum tillage management zones had significant higher ($p \leq 0.05$) organic matter, total organic (TOC) and total nitrogen content (Table 1.).

Table 1. Descriptive statistics of soil properties according to the different tillage systems. CV larger than 0.3 and significant differences are highlighted.

Field	Variables	Mean	Median	SD	CV (%)	Min	Max	Range
Conventional tillage	pH (water)	6,79a	6,80	0,09	1,37	6,70	6,88	0,18
	Organic matter (%)	**1,98a**	1,93	0,15	7,55	1,88	2,15	0,28
	Total organic carbon (% by weight)	**2,59a**	2,80	0,52	20,18	1,90	3,40	1,50
	Total Nitrogen g/kg	**1,37a**	1,35	0,11	8,01	1,28	1,48	0,20
	Phosphorus (M3) mg/kg	73,38a	72,30	15,96	22,70	58,73	89,13	30,40
	Potassium (exch.) mmol+/kg	3,37a	3,33	0,56	16,67	2,85	3,93	1,08
	Calcium (exch.) mmol+/kg	102,43a	102,78	12,41	12,64	90,18	114,33	24,15
	Magnesium (exch,) mmol+/kg	16,93a	17,13	3,49	20,54	13,43	20,25	6,83
	Cation Exchange Capacity mmol+/kg	137,42a	138,28	19,00	14,19	118,63	155,35	36,73
	Clay (%)	18,54a	18,18	1,91	10,30	16,90	20,55	3,65
	Soil penetration resistance up to 20 cm (MPa)	1,09a	0,93	0,42	**38,62**	0,53	1,69	1,16

Minimum tillage	pH (water)	6,79a	6,78	0,06	0,85	6,75	6,85	0,10
	Organic matter (%)	**2,41b**	2,28	0,40	15,73	2,10	2,85	0,75
	Total organic carbon (% by weight)	**3,05b**	3,10	0,20	6,48	2,60	3,30	0,70
	Total Nitrogen g/kg	**1,63b**	1,55	0,25	14,83	1,43	1,90	0,48
	Phosphorus (M3) mg/kg	75,94a	74,13	16,18	21,46	61,73	91,98	30,25
	Potassium (exch.) mmol+/kg	3,58a	3,63	0,24	6,63	3,33	3,78	0,45
	Calcium (exch.) mmol+/kg	113,04a	116,35	25,12	22,40	87,68	135,10	47,43
	Magnesium (exch,) mmol+/kg	17,92a	17,55	4,39	24,74	13,95	22,25	8,30
	Cation Exchange Capacity mmol+/kg	156,07a	160,28	32,91	21,24	122,30	185,63	63,33
	Clay (%)	18,91a	19,15	2,71	14,41	16,23	21,35	5,13
	Soil penetration resistance up to 20 cm (MPa)	1,22a	1,13	0,48	**39,26**	0,53	2,08	1,55

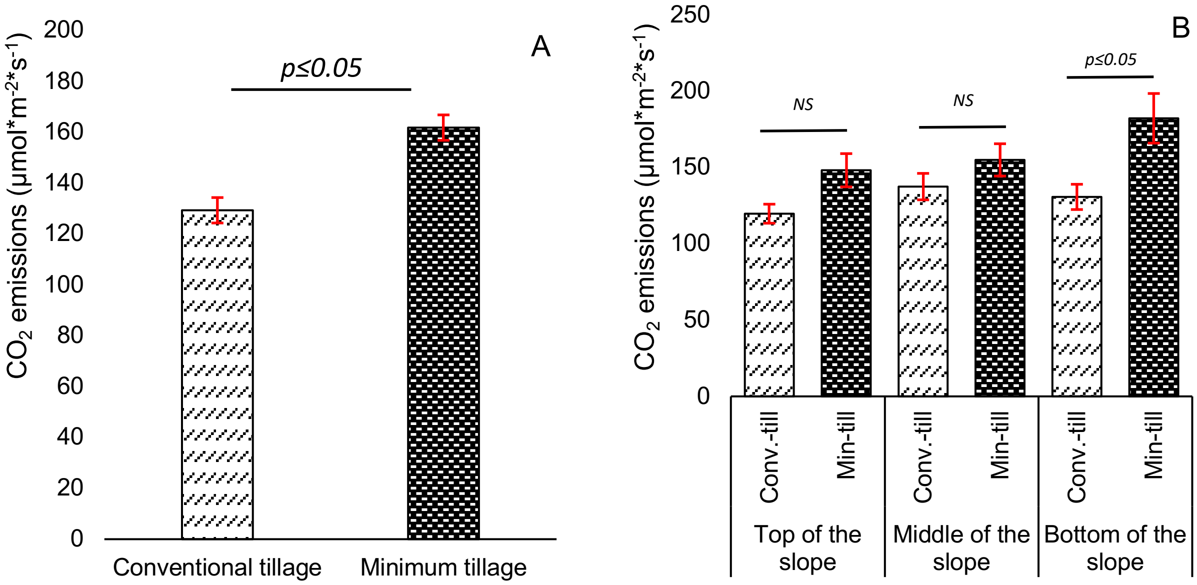
The soil properties of the pre-defined measurement points follow similar tendencies, as was observed in the whole field (Table 2.). The organic matter content and total organic carbon were significantly higher ($p \le 0.05$) in the minimum tillage system than in the conventional tillage system in all slope parts at each measurement point. Although the total nitrogen and soil penetration resistance were also higher in the minimum tillage systems than in the conventional tillage systems in three slope parts, the differences were not significant at $p \le 0.05$ significance level (Table 2.).

Table 2. Difference between soil properties in three pre-defined points.

Variables	Top of the slope		Middle of the slope		Bottom of the slope	
	Conv.-till	Min-till	Conv.-till	Min-till	Conv.-till	Min-till
Organic matter (%)	**1.87a**	**2.23b**	**1.93a**	**2.30b**	**2.37a**	**2.70b**
Total organic carbon (% by weight)	**2.33a**	**3.04b**	**2.38a**	**3.12b**	3.07a	2.99a
Total Nitrogen g/kg	1.27a	1.50a	1.37a	1.60a	1.47a	1.77a
Soil penetration resistance up to 20 cm (MPa)	1.08a	1.49a	1.09a	1.21a	0.99a	1.21a

Soil carbon-dioxide emissions under different soil management practices

The carbon dioxide (CO_2) emissions of different tillage systems showed significant differences ($p \le 0.05$). The CO_2 emissions of the conventional tillage system were 129.36±4.51 μmol m^{-2} s^{-1}, while the minimum tillage systems emitted 161.87±7.44 μmol m^{-2} s^{-1} (Figure 2A.). Comparing the soil carbon dioxide emissions at the different parts of the slope, it was found that the minimum tillage system had larger emissions, but a significant difference ($p \le 0.05$) was only observed at the bottom of the slope. The CO_2 emissions of the conventional tillage system were 119.77±6.24 μmol m^{-2} s^{-1} at the top of the slope, while the minimum tillage system had 148.27±10.90 μmol m^{-2} s^{-1}. At the middle of the slope, 137.53±8.67 μmol m^{-2} s^{-1} was measured in management zones applied tillage, and conversely, 155.04±10.59 μmol m^{-2} s^{-1} CO_2 emissions were observed in the minimum tillage farming system. The carbon dioxide emissions in the minimum tillage system were 182.31±16.27 μmol m^{-2} s^{-1}, while 130,78±8.28 μmol m^{-2} s^{-1} carbon dioxide emissions were detected in the conventional tillage system at the bottom of the slope (Figure 2B.).



NS, No significant difference at p≤0.05

Figure 2. Mean ± standard error of carbon-dioxide emissions in different tillage systems (A) and according to slope parts (B).

Pearson correlation analysis – Relationships among soil CO_2 emissions and soil and environmental properties in different slope parts.

The Pearson correlation analysis showed that the soil penetration resistance, the soil moisture content, air pressure and the relative humidity were the most concerned driver factors behind the CO_2 emissions in case of all slope parts. Significant strong positive correlations (0.90 and 0.92) were observed between CO_2 emissions and soil moisture content in case of top and middle of the slope. The correlation was negative between relative humidity and CO_2 emissions, but its strength varies between 0,68 and 0,80. Negative correlations were found between soil penetration resistance and CO_2 emissions, but its strength was exclusively significant in the middle of the slope. Moderate negative correlations were observed between air pressure and carbon dioxide. Air temperature and total organic carbon showed week and negative correlation in the case of all parts of the slope (Table 3.).

Table 3. Pearson correlation coefficients between soil CO_2 emissions and other variables in the different parts of the slope.

Variables	Top of the slope	Middle of the slope	Bottom of the slope
		CO_2 emissions	
Air temperature (AT)	-0.22	-0.18	-0.09
Air pressure (AP)	-0.45	-0.52	-0.51
TOC%	0.18	0.02	0.20
Soil penetration resistance (PR)	-0.29	-0.91*	-0.50
Soil moisture content (GWC)	0.90*	0.92*	0.63
Relative humidity (RH)	-0.68	-0.80*	-0.75**

*, significance level at p≤0.05, **significance level at p≤0.1,

Model for predicting the contribution of each independent variable in CO_2 emissions

The developed models for the top of the slope were based on two variables, while three are the basis of the model for the middle and bottom of the slope (Table 4). The factors for which the statistical significance at level of p≤0.05 was not confirmed were TOC (total organic carbon) and PR (soil penetration resistance) in case of model for top of the slope, PR for model for middle of the slope and AT (air temperature) in case of bottom of the slope model.

Table 4. Regression coefficients and probability levels for the generated models.

Variables	Models		
	Top of the slope	Middle of the slope	Bottom of the slope
	Adjusted R^2=0.748	Adjusted R^2=0.995	Adjusted R^2=0.931

	b	p	Sig.	b	p	Sig.	b	p	Sig
TOC	-	-	-	14.976	0.062	p≤0.1	368.608	0.021	p≤0.05
AP	-0,297	0.028	p≤0.05	-0.329	0.001	p≤0.05	-1.120	0.027	p≤0.05
PR	-	-	-	-	-	-	382.943	0.064	p≤0.1
AT	-18.185	0.037	p≤0.05	-18.630	0.002	p≤0.05	-	-	-

Multicollinearity was not identified between the independent variable in the models. The VIF threshold values were not higher than 5 in any models. Therefore multicollinearity does not exist in these regression models (Table 5.).

Table 5. Variance Inflator Factor (VIF) value between the independent variables in the models.

Variables	Models		
	Top of the slope	Middle of the slope	Bottom of the slope
TOC-PR	-	-	1.285
AP-PR	-	-	5.000
AT-AP	1.706	1.285	-
AT-TOC	-	1.081	-
AP-TOC	-	1.067	1.047

Forecasting properties of models

The proper functioning of models was verified by comparing the obtained forecasts with the actual carbon dioxide emissions for the different parts of the slope. All models performed well. They predicted the CO_2 emissions with high accuracy (Figure 3.). Four measures of ex-post forecast accuracy showed that the models enable determining the soil CO_2 emissions under controlled laboratory conditions (Table 6.).

Table 6. Ex-post predictive measures in different models.

Error Type	Model		
	Top of the slope	Middle of the slope	Bottom of the slope
RAE [-]	0.14	0.02	0.08
RMSE [$\mu mol*m^{-2}*s^{-1}$]	20.40	2.27	15.23
MAE [$\mu mol*m^{-2}*s^{-1}$]	15.93	1.61	13.92
MAPE [%]	10.77	1.30	12.92

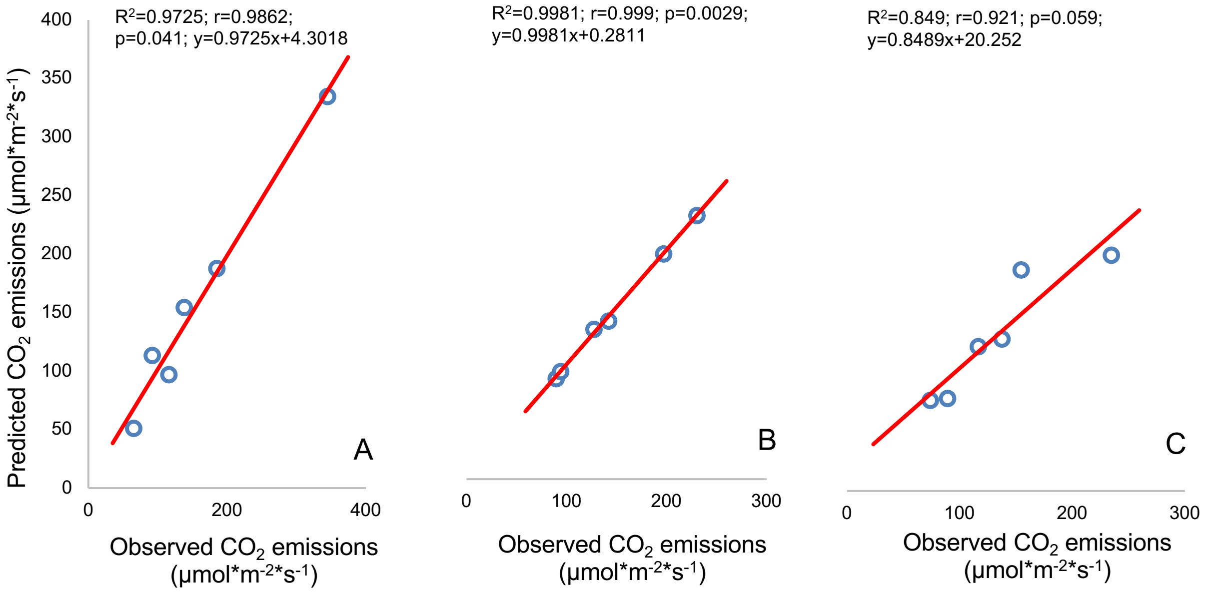


Figure 3. The scatter plot between observed and predicted emission values according to slope parts (Top – A; Middle – B; Bottom – C).

Discussion and conclusions

Our results revealed that the different tillage practices influence the soil CO_2 emissions, but their impact and amplitude vary according to the slope parts. The study reported that the minimum tillage practice had 20 precent higher CO_2 emissions than conventional tillage practice (Figure 2A.), but the difference has been changing according to the part of the slope (Figure 2B.). Our results are in alignment with the findings of Cheng-Feng et al. (2012) and Plaza-Bonilla et al. (2014). They also reported lower CO_2 emissions under tillage management compared to no-till systems. Wang et al. (2017) and Hu et al. (2021) reported that the CO_2 emissions decreased exponentially with slope gradients in controlled erosion plots, which is in line with our findings in the case of minimum tillage management zones.

The impact of the environmental factors and soil carbon content on the soil CO_2 emissions are well studied (Oertel et al. 2016; Smith et al. 2018). However, the role of air pressure in soil CO_2 emissions is rarely mentioned in literature data. Reicosky et al. (2008) found that the lower air pressure supports the higher soil emissions due to the reduced counter-pressure in the soil. The application of the multiple linear regression model for yield prediction is a well-researched field (Piekutowska et al. 2021), but the usability of this statistical method in the prediction of CO_2 emissions was also confirmed by Singh et al. (2022) and Kulmány at el. (2022).

In this research, CO_2 emissions were monitored on soil tubes derived from two different tillage systems under laboratory conditions. The first was a tillage farming system, while the second was a minimum tillage farming system. This research showed that CO_2 emissions were higher in the minimum tillage farming system than in conventional farming systems, but their amplitude changed according to the slope position. Considering the collected different environmental and soil factors and their impact on soil emissions, the findings of this study could help scientists and decision-makers to predict the soil CO_2 emissions. Thus, contributing to the drawing up mitigation strategies to minimize the total GHG emissions from the agricultural sector.

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