SZENT ISTVÁN UNIVERSITY
GÖDÖLLŐ

MECHANICAL ENGINEERING PhD SCHOOL

Effect of tillage machines and processes on soil CO_2 emission

Thesis of PhD work

János Péter Rádics

Gödöllő, Hungary
2015

Doctoral school Denomination: Mechanical Engineering Doctoral School

Science: Agricultural Engineering

Leader: Prof. Dr. István Farkas
Professor, DSc,
Faculty of Mechanical Engineering,
Szent István University, Gödöllő, Hungary

Supervisor: Prof. Dr. László Fenyvesi
Professor, PhD,
Institute of Mechanics and Machinery,
Faculty of Mechanical Engineering,
Szent István University, Gödöllő, Hungary

Co-supervisor: Prof. Dr. István J. Jóri
Professor, CSc,
Department of Machine and Product Design
Faculty of Mechanical Engineering,
Budapest University of Technology and Economics

……..……………………… ……………………………..

Affirmation of head of school Affirmation of supervisors

CONTENTS

1. INTRODUCTION, OBJECTIVES

The palpable imminence of the adverse effects of climate change imposes increasingly urgent obligations on researchers and decision-makers alike. The continuously increasing temperature, and the ever more frequent extreme weather conditions make the need for intensive international cooperation increasingly urgent and obvious. Measures need to be taken to mitigate these effects and to curb, stop, or reverse their speed of progress, since global climate change is the greatest challenge ever faced by mankind (JOLÁNKAI and BIRKÁS, 2005).

The change in the climate of our planet is assumed to have been primarily caused by the increase in the concentrations of greenhouse gases (GHG) that naturally regulate the greenhouse effects of Earth's atmosphere. Anthropogenic GHG emissions are primarily induced by energy generation, industry, and intensive agriculture and forestry.

Agricultural activities form the foundation of food production for Earth's human population. While adverse effects need to be mitigated, this must not decrease production, as this would arguably have catastrophic consequences. Research must focus on mitigating effects that contribute to climate change, while at the same time maintaining the quantities of primary commodities produced. CO_2 emission into the atmosphere caused by land use and decreasing carbon stock has been an increasingly important issue since the 1980-ies. In order to accurately understand the carbon cycle of tilled soils and model the process, the various cause–effect relationships need to be studied separately. The large body of accumulated research material on the emissions of various tillage systems and procedures facilitates the analysis and understanding of the soil's carbon cycle. Detailed mathematical models are readily available for describing the absolute values of the CO_2 cycles of forest soils and fields, but sufficient knowledge is still lacking for modeling the CO_2 emissions of different tillage procedures and systems and accurately determining their contribution to the soil's CO_2 emission and the related change in carbon stock.

Based on the above, I formulated the following objectives:

- Develop a measurement procedure in line with the statements found in the literature for quantifying the CO_2 emissions of tillage procedures to enable the relatively quick and easy determination and comparison of individual tillage procedures.
- Measure changes in soil CO_2 emissions caused by different tillage procedures in the available test areas.
- Develop a mathematical model suitable for determining the emissions of the various tillage procedures.
- Generalize the model and determine the consolidated emission of tillage technologies.

2. MATERIALS AND METHODS

Achieving the goals set out in the research hypothesis required developing a new study procedure, performing on-site measurements in fields, and develop the foundations of the emissions model.

2.1. Field measurements – general description

Soil CO_2 emissions were studied using a chamber measurement procedure. The procedure consists of using a chamber located above soil level to accumulate CO_2 leaving the soil due to soil respiration, and studying the gas concentration in samples taken from the chamber or directly within the chamber. The measurement data, the area covered by the chamber, the chamber volume, and the incubation time can then be used to calculate the CO_2 emission per area unit.

Plots with different tillage methods were assigned in the study areas excluding the turning area, and incubation chambers were placed in each directly after cultivation. This made sure that the accumulation of CO_2 emissions started immediately after cultivation. For each measurement, the emission of the untilled (reference) area was also determined and used as the reference (zero) value for that specific area and soil type, used when evaluating the effect of tillage on the studied area. Atmospheric CO_2 concentration was a parameter used for every measurement. This approach made sure that only the CO_2 emission caused by tillage was taken into account during the calculations.

In order to represent the heterogeneity of the area, each measurement chamber was sunk into the soil at a randomly selected point of the area for each cycle, which ensured that nothing interfered with the soil’s microclimate until the start of the measurement. The measurement values were averaged and processed on a computer.

After the various types of tillage, short and medium duration measurements were taken to investigate soil CO_2 emission. CO_2 emission was measured 1–5 hours after tillage for short measurements and 28–30 hours after tillage for medium duration measurements. The sampling intervals were initially determined based on the estimated probable emission intensity, and subsequently – based on previous measurements – in a way to best optimize emission representation.

2.2. The experimental areas

CO_2 emission studies were conducted in the areas of Enying Agrár Zrt. in Lajoskomárom, county Fejér, and the areas of the farmer Rádics Balázs in Mesztegnyő, county Somogy. The areas of Enying Agrár Zrt. used for the study are loam soils with a high organic content. From among the areas used by farmer Rádics Balázs, the areas Mesztegnyő “T1” and Hosszúvíz “A1” are sandy soils, while Mesztegnyő “H1” and Mesztegnyő “H2” are clay soils, both types with a low organic content.

Table 2.1. Summary data of *short duration* measurements

Meas. No.	**Operation / Date**		**Area**	**Weather and soil conditions**	**Tillage machine**	**Tillage Depth [cm]**
1.	Stubble mulching on crop stubble	07.15.2003.	Enying “S4”	Dry, windy weather, 28°C Dry soil	Rába–IH disk harrow + Güttler roller	**14–16**
					Komondor mulch cultivator	**14–16**
					Kverneland CLE chisel plough	**24–26**
2.	Primary tillage on maize stubble	09/23/2003	Enying “S10”	Dry, windy weather, 20°C Dry soil	Rába–IH disk harrow + Güttler roller	**19–21**
					Kverneland BB 115 moldboard plough	**24–26**
					Kverneland CLE chisel plough	**33–37**
		10/16/2003		Dry, windy weather, 16°C Wet soil	Komondor mulch cultivator	**18–20**
3.	Stubble mulching on crop stubble	06/06/2007	Mesztegnyő “H1”	Dry, sunny weather, 26–28°C Humid soil	Symba X-press disk harrow	**12–14**
4.	Stubble mulching on rapeseed stubble	06/07/2007	Mesztegnyő “A1”	Dry, sunny weather, 29–31°C, Humid soil	Pöttinger Synkro field cultivator + Pöttinger Lion rotary harrow	**16–18**
					Pöttinger Synkro field cultivator	**22–25**
5.	Stubble mulching on crop stubble	07/14/2007	Mesztegnyő “H1”	Dry, sunny weather, 25–28°C, Humid soil	Chisel plough	**38–45**
					Pöttinger Synkro field cultivator	**22–25**
					Pöttinger Synkro field cultivator + Pöttinger Lion rotary harrow	**16–18**
6.	Stubble mulching on rapeseed stubble	07/15/2007	Mesztegnyő “A1”	Dry, sunny weather, 29–31°C, Humid soil	Symba X-press disk harrow	**12–14**
7.	Primary tillage on corn stubble	08/09/2011	Mesztegnyő “T1”	Dry, sunny weather, 28–31°C, Humid soil	Custom chisel plough	**38–42**
8.	Stubble mulching on sunflower stubble	09/17/2011	Mesztegnyő “H1”	Dry, sunny weather, 25–28°C, Dry soil	Lemken Thorit field cultivator	**14–16**

Table 2.2. Summary data of *medium duration* measurements

Meas. #	**Operation / Date**	**Area**	**Weather and Soil Conditions**	**Tillage Machine**	**Tilling Depth [cm]**
9.	Stubble mulching on crop stubble 07/15/2004	Enying “S4”	Dry, sunny weather, 28°C, Dry soil	Kuhn Optimer compact disk harrow	**12–14**
				Kverneland BB115 moldboard plough	**24–26**
10.	Stubble mulching on crop stubble 08/18/2014 – 08/09/2014.	Mesztegnyő “H2”	Dry, sunny weather, 28°C, Humid soil	Pöttinger Synkro field cultivator	**20–22**
				Vogel&Noot reversible plough	**32–35**

2.3. The measurement procedure

A fundamental task during the development of a measurement process delivering reliable measurement data was the selection of a suitable measurement instrument and the design of the incubation chamber used for collecting soil-emitted CO_2.

The instrument was selected after comparing two instruments for measuring CO_2 concentration: an INNOVA 1312 Photoacoustic Multi-gas Monitor automated measurement system, and a TESTO 535 instrument placed directly in the chamber.

Designing the chambers

The first and second measurement series were performed using polyethylene vessels with a truncated cone shape and a volume of 8300 cm^3. The chambers were not moved during the entire duration of the measurement. The incubation time was 1.5–4 hours. Experience gained during the measurements showed that due to eventual saturation and impact to the soil's microclimate, the method of not ventilating the chambers until the end of the measurement was not suitable for getting reliable data from longer measurements.

For this reason, two measurement processes were used for the first medium-duration measurement. Half of the measurement chambers were left in place during the entire duration of the measurement (cumulating procedure). The other half of the chambers were ventilated between measurements (ventilated method).

Based on the experiences of the initial measurements and due to the tillage operations resulting in a larger aggregate size, I decided to increase the area covered by the chamber, and designed and made new chambers. The new chambers were selected to be 300×300×350 mm square prisms. Due to the significantly increased volume/surface ratio, fans were placed inside the chambers. Comparative measurements were then performed using the truncated cone chambers and the square prism chambers to investigate whether results obtained with the different chambers are comparable.

Evaluating the Measurement Results

Both instruments display measurement results in [ppm], equivalent in SI units to [µmol/mol]. During data processing, the concentration values measured in the chambers need to be recalculated for unit time and unit area to arrive at the specific soil CO_2 emission, using the following formula (MEYER *et al.*, 1987; WIDÉN & LINDROTH, 2003):

$$F_{CO_2} = \frac{dC}{dt} \frac{V\,p\,M}{R(273{,}15 + T)A}, \tag{2.1.}$$

where F_{CO_2} is the CO_2 emission intensity $\left[\frac{g}{m^2 h}\right]$, dt is the measurement duration [h], dC is the change in CO_2 concentration during the measurement $\left[\frac{mol}{mol}\right]$, V is the volume of the measurement chamber $[m^3]$, p is the atmospheric pressure $[Pa]$, M= 44,01 $\left[\frac{g}{mol}\right]$ is the molar mass of CO2, R= 8,314 $\left[\frac{J}{mol*K}\right]$ is the universal gas constant, T is the temperature $[\,^oC]$, and A is the soil surface covered by the measurement chamber $[m^2]$.

2.4. Fundamentals of emission modeling

The emission model was designed based on a mathematical description of the emission process occurring after tillage, using general laws of nature. The temporal change in soil CO2 emission caused by tillage is the result of enzyme reactions catalyzed by oxygen mixed into the soil, combined with changes in the speeds of enzyme reactions caused by changes in soil temperature. Reactions catalyzed by enzymes are usually characterized using the Michelis–Menten kinetics (NYESTE, 1988); its stoichiometric equation can be used to derive a differential equation for end product formation that yields the following:

$$C_{talaj}(t) = C_0\, e^{-k_1 t}\,, \tag{2.2.}$$

where C_{talaj} is the mobilizable carbon content of the soil $\left[\frac{g}{m^2}\right]$, t is the time $[h]$, C_0 is the initial mobilizable carbon content of the soil $\left[\frac{g}{m^2}\right]$, and k_1 is a model parameter $[-]$.

An important factor during the approximation of measured data is the temperature of the soil surface. At the same time, capturing the direct effect of heat by using a temperature-dependent variable is not called for. The measured emission values influenced by various environmental effects and soil characteristics already contain the temperature parameter: although the catalyzed enzyme-kinetic reaction can be expected to be predominant, emission is also a function of temperature. More accurate emission values can be obtained using a model that takes into account the change in temperature during the day. The change in soil temperature can be described with the following function as stated by VÖLGYESI (1982):

$$T = T_0 + A\sin\left(\frac{2\pi}{t_0}t + \beta\right), \tag{2.3.}$$

where T is the soil temperature $[\,^oC]$, T_0 is the mean temperature of the soil $[\,^oC]$, A is the amplitude of change in soil temperature $[\,^oC]$, t_0 is the duration of the period $[h]$, t is the time $[h]$, and β is the phase shift $[h]$.

I used the relationships described above to develop the emission model and perform regression analysis on the measured data.

3. RESULTS

The specified goals were attained based on the study approach described in the previous chapter, using the devices and measurement instruments described. This chapter contains the measurement results, the output of data processing, and the conclusions drawn.

3.1. The measurement procedure – a comparative evaluation

One important objective of the research was to develop a flexible and reliable measurement procedure for measuring soil CO_2 emission. This chapter highlights the major results of the comparison between the measurements performed using the instruments and measurement procedures described in the previous chapter.

Results of the comparative measurements performed with the procedures used

A comparative study of the TESTO and INNOVA measurement instruments (Figure 3.1) shows that until the first measurement, the data obtained for the concentration in the chamber reflect the same rate of increase regardless of which instrument is used. After the first measurement, however, results obtained from the two instruments show totally diverging rates. Based on the literature, an increase in chamber concentration was to be expected several hours after tillage, but this was only reflected in the values obtained with the TESTO instrument. In contrast, the values obtained with the INNOVA instrument showed only a minuscule increase in chamber concentration, and even a decreasing concentration in some cases. The decrease and stagnation of gas concentration in the chamber is probably caused by ventilation inherent to the INNOVA instrument. This ventilation causes a significant change in the CO_2 concentration of the air enclosed by the chamber.

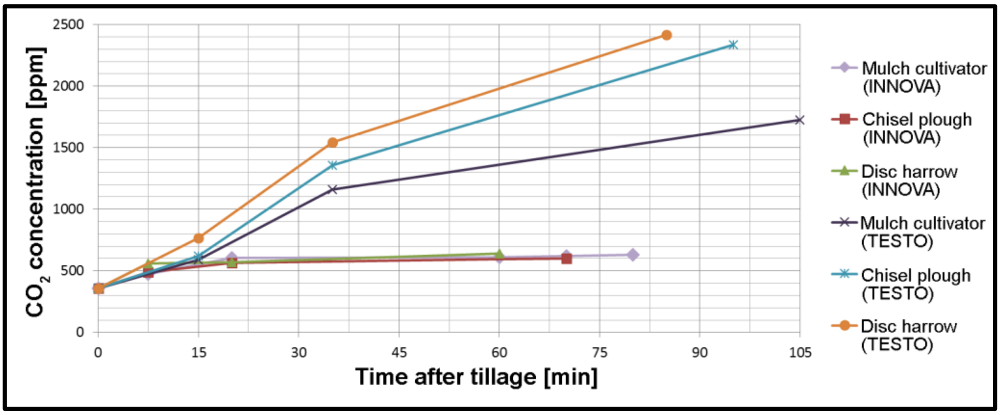


Figure 3.1 Measured values of soil CO_2 emission after different types of tillage (Measurement 1)

Due to the above anomalies experienced with the INNOVA measurement system, only results obtained with the TESTO 535 instrument were taken into account. The measurement results obtained using the INNOVA system were regarded as faulty measurements and discarded.

Comparing the cumulating and the ventilated measurement procedure

The anomalies experienced with the cumulating measurement procedure are illustrated using the results of Measurement 2 (Figure 3.2). The results for plots tilled with disk harrow and chisel plough correspond to the trends predicted by the theory. However, decreasing chamber CO_2 concentration was measured on the untilled plot (reference measurement) and on the ploughed plot. The negative emission value can not be interpreted because it would require the soil to be a CO_2 sink.

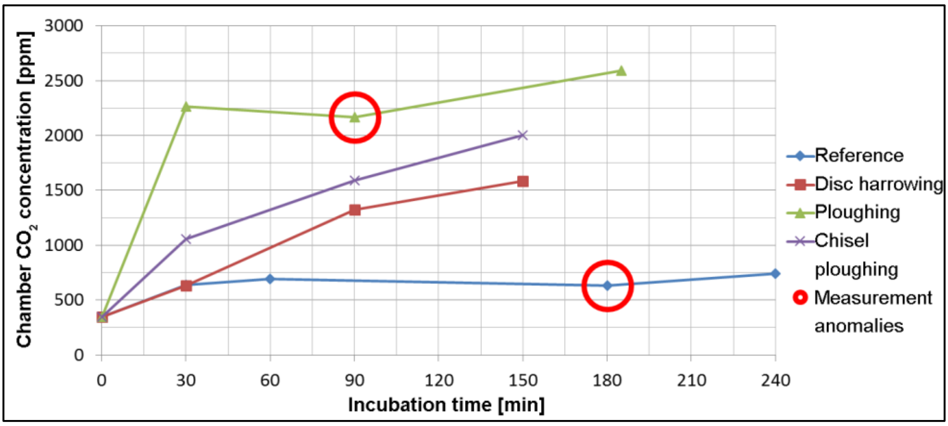


Figure 3.2 Anomalous measurement values in chambers with long incubation (Measurement 2)

The phenomenon is explained by the fact that air above the studied plot caused the air around the chamber to flow from the chamber towards the soil. For this reason, measured values obtained after a decrease in chamber concentration can not be evaluated because the degree of decrease in chamber concentration caused by external impacts is not known.

At the same time, the sequence of different types of tillage by emission on the different plots corresponds to the intensity of soil disturbance effected by the different types of tillage. In Figure 3.3, the cumulating measurement procedure is represented by the actual values measured, while values for the ventilated procedure were decreased by the atmospheric CO_2 concentration measured when the chamber was positioned. Then the obtained values were summarized for each measurement point. This means that ventilated chambers are represented by a theoretical cumulated concentration. The measured values were approximated by linear regression, starting at time zero from the point corresponding to the atmospheric concentration. As can be seen, there is a significant deviation between values measured with the two procedures, which assumes different CO_2 concentrations for identical tillage types.

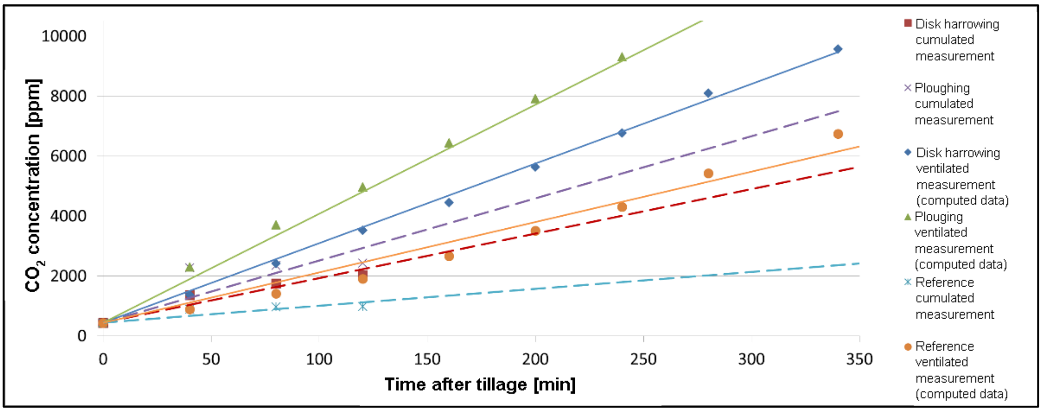


Figure 3.3. Comparison of cumulating and ventilated measurements for Measurement 9, based on linear regression of the measured values

Despite the deviations of the measured values, the gradients of their approximation functions for the different types of tillage show the same sequence for each set of measurement series, regardless of whether the series consisted of cumulated or ventilated measurements. The reason for this is that samples taken at the same time and on the same study area are subject to identical external influences, and the adverse effect of the chamber on the soil’s microclimate is also identical. As can be seen, the gradients of the linear polynomials fitted to the cumulative results obtained with different measurement procedures depend on the characteristic aggregate size and aeration, as do the occurrences of measurement anomalies. Accordingly, although measurement data obtained from measurements with long incubation time and no ventilation can not be used for determining the quantities of CO_2 emission, they are suitable for comparing the different measurement procedures and ranking the different types of tillage.

Determining the minimum incubation time

The ventilated measurement method lends itself for performing medium-term and long-term field studies. The use of a large number of chambers makes it necessary to decrease the incubation time. The shorter incubation time, in turn, causes reading uncertainties that have a significant effect on the total measurement error. In order to determine the minimum required incubation time, I investigated the sensitivity of emission values calculated from the measurement results to errors in chamber CO_2 concentration measurements within the typical reading error range (1–5ppm). I found that a minimum incubation time of 12 minutes is required in order to keep measurement errors under 5 percent. I therefore determined a minimum incubation time of 15 minutes.

Comparison of methods: truncated cone-shaped vs. Prism-shaped chambers

Figure 3.4 shows the emission intensity values determined from measurement data obtained using ventilated and unventilated measurement chambers.

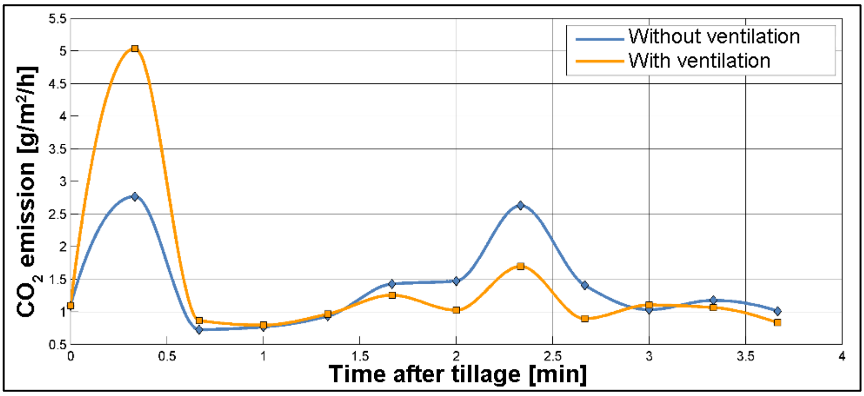


Figure 3.4. Comparison of measurement results obtained using truncated cone-shaped chambers with and without ventilation (Measurement 7)

The quantities calculated from the measurement values are summarized in Table 3.1. As shown in the table, the measurement results of the two chambers differ by 4.1 percent in terms of the quantities of emitted CO_2.

Table 3.1. Emission data of ventilated and unventilated measurement chambers

	Emitted CO_2 quantity during measurement [g/m^2]	**Deviation of emitted CO_2 quantity [%]**
Unventilated chamber	5.2546	100
Ventilated chamber	5.4709	104

Figure 3.5 shows the intensity values calculated from measurements performed on sandy soil. Based on the measurement results, the emission intensities measured using different measurement chambers are very similar.

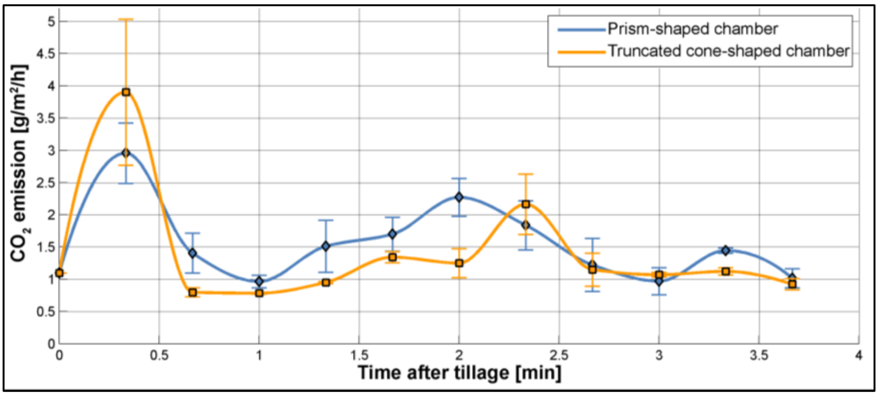


Figure 3.5. Emission intensity and standard deviation using different chambers

Table 3.2. Comparison of emission data measured using different chambers

	Emitted CO_2 quantity during measurement [g/m^2]	**Deviation of emitted CO_2 quantity [%]**
Truncated cone chamber	5.3481	100
Prism chamber	5.9015	110

The high measured emission intensity at the first measurement point in the truncated cone-shaped chamber having a smaller volume may also have been caused by soil heterogeneity, as also reflected in the high standard deviation of the measurement data. The results also show that for the entire measurement interval, the variance of the results obtained for the prism-shaped chamber are much smaller than those obtained using the truncated cone-shaped chamber. Accordingly, the use of prism-shaped chambers yields more uniform results, which is also due to the larger sampling area covered by the chambers.

3.2. Results obtained from short-duration measurements

The results obtained from short-duration measurements show that CO_2 emission measured directly after using different tillage machines is primarily influenced by tillage intensity, the efficiency of the compacting device used, and the size of the aggregate created. The effect of tillage intensity is shown in Figure 3.6. The sequence of studied areas ordered by increasing CO_2 emission is the following: untilled area, disking, chisel ploughing, ploughing. The most intensive emission was measured along the shanks of the chisel plough.

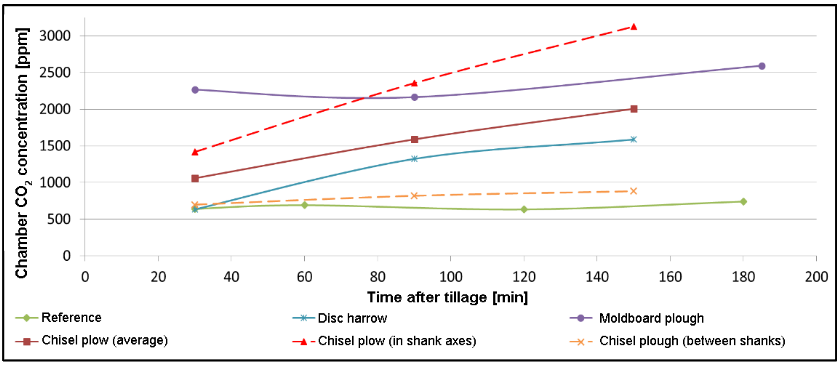


Figure 3.6. CO_2 concentration after different types of tillage, Measurement 2

The effects of the characteristic aggregate sizes are shown in Figure 3.7 and Figure 3.8. In the case of Measurement 4 (Figure 3.7.) performed on sandy soil using a cultivator complemented by a rotary harrow, the measured emission values were significantly higher than on areas where only a cultivator was used. This led me to conclude that the crushing and mixing effect of the rotary harrow, combined with the creation of a soil structure with small particle size, made the atmospheric oxygen content more accessible to aerobic microorganisms. The opposite was found on loamy clay soil during Measurement 5 (Figure 3.8). In this case, the clod-crushing effect of the rotary harrow was less marked, and the clod fraction was predominant. For this reason, microorganisms in the clods could access oxygen slower or not at all.

The emission on clay soil was significantly more intensive along the shanks of the chisel plough as compared to all other types of tillage. At the same time, it can be seen that values measured between the shanks significantly exceed the values measured on the untilled area, the highly probable reason being that crack propagation in the loamy clay soil during scarification was more intensive, which in turn made more oxygen accessible to microorganisms.

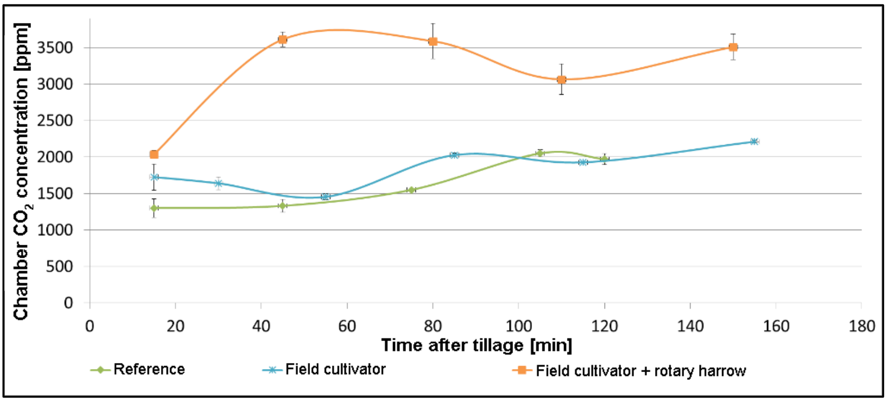


Figure 3.7. The effect of a rotary harrow used on sandy soil (Measurement 4)

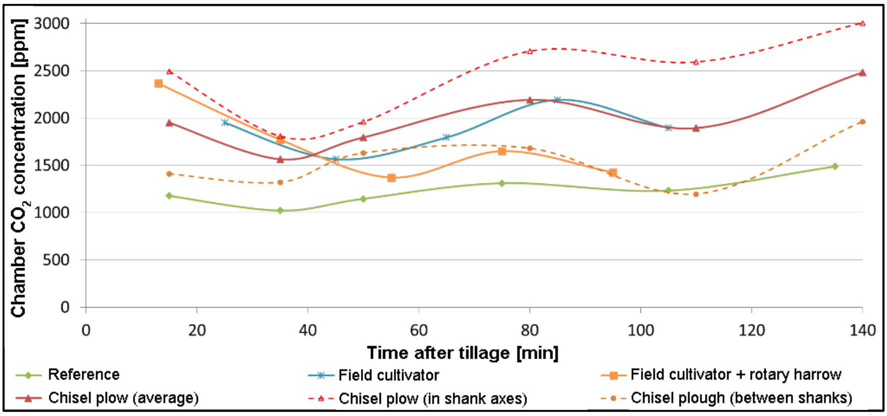


Figure 3.8. Loamy clay soil tilled at various intensities (Measurement 5)

3.3. Results obtained from medium-duration measurements

The emission intensity values calculated from medium-duration measurement results are presented in Figure 3.9 and Figure 3.10. The data clearly show that, in accordance with the reaction kinetics, the oxygenated air mixed into the soil directly after tillage causes a fluctuating but intensive emission that then continuously subsides to values similar to those of untilled soil. The trends of intensity values show that in addition to an exponential decrease, the emission intensity of the tilled area also follows the fluctuations in temperature. An observation made during the first medium-duration measurement (Figure 3.9) was that after 11–15 hours, the curves obtained for tilled and untilled areas practically merged. This is in line with statements found in literature: decay on a similar time scale was found (ELLERT & JANZEN, 1999) during studies made on Canadian chernozem soil.

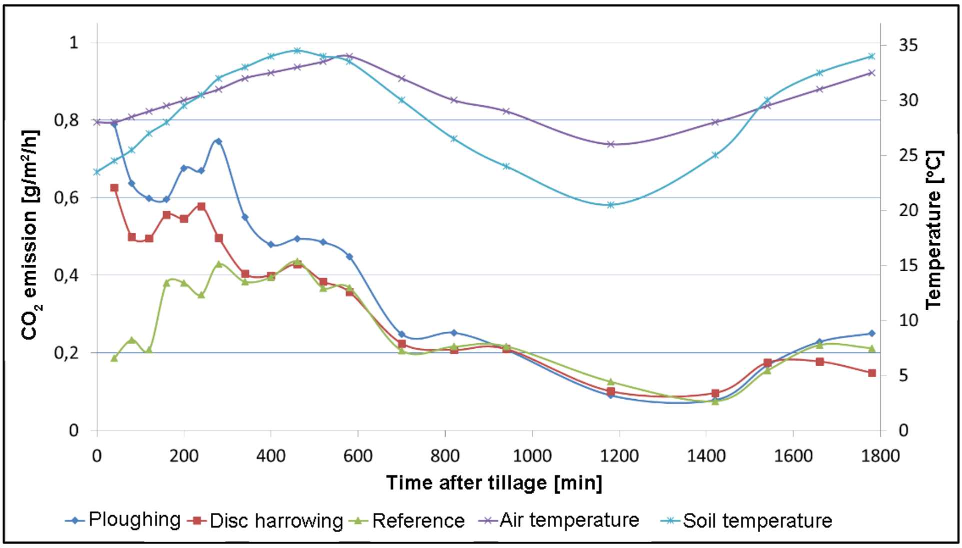


Figure 3.9 Measured emission and temperature data using polynomial interpolation (Measurement 9)

No such clear merging of the emission values was observed during Measurement 10 (Figure 3.10) because the probable period of merging is during the night when the significant decrease in soil temperature also greatly decreases emissions.

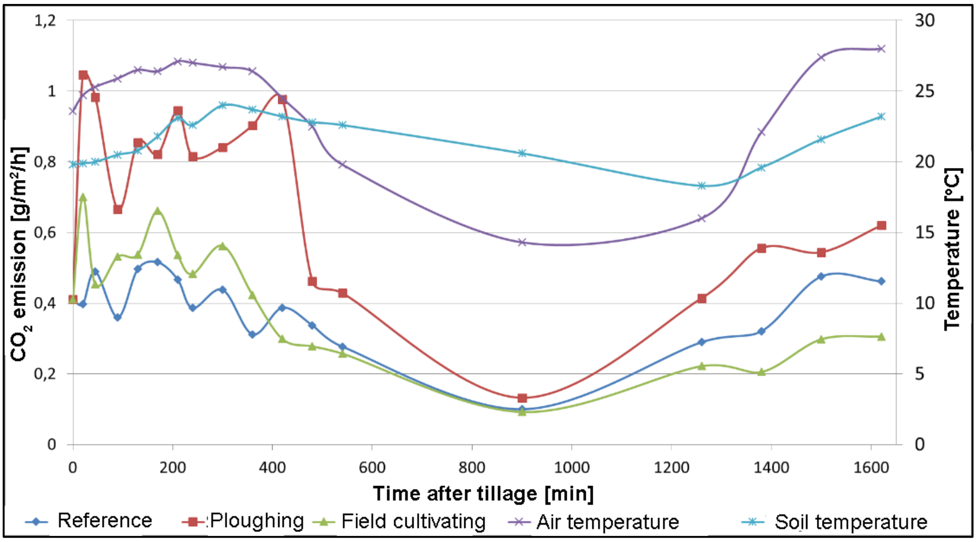


Figure 3.10 Measured emission and temperature data using polynomial interpolation (Measurement 10)

The probable cause of fluctuations observable in the curve trajectories is spatial heterogeneity. This is borne out by the fact that curves with smoother trajectories were obtained with the cumulating measurement procedure used for previous measurements when applied for longer measurements at the same measuring point. When using the ventilated method, the sampling locations are not identical, and spatial heterogeneities are also represented as shown by the measured data, so fitting the emission model delivers realistic, averaged emissions characteristic for the studied area. The values of the reference curve clearly indicate that the reaction-kinetic member of the model can be neglected for untilled soil, as its emission shows a similar trajectory to that of the soil temperature curve, apart from a phase shift. It can also be observed that the emission maximum of untilled soil shows a better coincidence with the air temperature maximum rather than with the soil temperature maximum.

3.4. Results obtained by developing the CO_2 emission model

The next step in achieving the stated goals was to create a model that best approximates the measured values and takes into account the physical and biochemical processes, followed by developing the regression analysis algorithm suitable for curve fitting. As discussed above, CO_2 emission after tillage is primarily influenced by the kinetics of the enzyme reaction catalyzed by oxygen mixed into the soil during tillage, combined with the temperature dependence characteristic for biochemical processes. Simply multiplying equations (2.2) and (2.3) describing these two laws of nature would yield a function similar to that describing damped oscillations. This would not be satisfactory for the case under discussion, because the enzyme reactions catalyzed by the oxygen of the air mixed with the soil always shift function values in a positive direction. Accordingly, the median of the model should exhibit an exponentially decreasing tendency, so overall, the CO_2 emission after tillage should be modeled with a function exhibiting an exponentially decaying amplitude and a sinusoidal periodicity describing the daily and annual temperature fluctuations. The emission model can hence be described as follows:

$$W = \left(\left(\frac{\left(Ae^{(t\,c_0)}\right)+h}{2} \right) \left(\sin(c_1\,t - c_2)\right) \right) + \left(\frac{\left(Be^{(t\,c_0)}\right)+h}{2} \right) + \left(C\,sin(c_3\,t)\right), \qquad (3.1.)$$

where W is the CO_2 emission $\left[\frac{g}{m^2h}\right]$, A is a coefficient that determines the initial value of emission [-], B is a coefficient that determines the initial minimum value of emission [-], C is a coefficient that determines the amplitude fluctuation over the year [-], t is the time passed since tillage [h], c_0 is a coefficient that determines the decay intensity of the emission [-], h is the maximum emission of the untilled area $\left[\frac{g}{m^2h}\right]$, c_1 is a coefficient that defines the cycle time of CO_2 emission for the untilled area [-], c_2 is a coefficient that defines the phase shift of the sinusoidal emission periodicity [-], c_3 is a coefficient that defines the annual cycle time of CO_2 emission for the untilled area [-], j is the minimum emission on the untilled area $\left[\frac{g}{m^2h}\right]$. Determining the coefficients for this model would constitute a complex mathematical problem and would also require a practically unfeasible amount of measurement data. On the other hand, the formula is overdetermined in terms of the amount of CO_2 emitted. Considering this latter fact as well as the durations and measurement points of the measurements performed, equation (3.1) can be simplified to yield equation (3.2) which describes a model that is easy to use in practice. The upper envelope of this model is an exponential function, while its lower envelope is a constant function that corresponds to the minimum emission value of the untilled area.

$$W = \left(\left(\frac{\left(Ae^{(tc_0)}\right) + h}{2}\right)(\sin(c_1 t - c_2) + 1)\right) + j \tag{3.2.}$$

where W is the CO2 emission $\left[\frac{g}{m^2 h}\right]$, A is a coefficient that determines the initial value of emission [-], t is the time passed since tillage [h], c_0 is a coefficient that determines the decay of emission intensity [-], h is the maximum emission of the untilled area $\left[\frac{g}{m^2 h}\right]$, c_1 is a coefficient that defines the cycle time of CO2 emission for the untilled area [-], c_2 is a coefficient that defines the phase shift of CO2 emission [-], j is the minimum emission on the untilled area $\left[\frac{g}{m^2 h}\right]$.

In order to determine the coefficients of the emission model, I used MATLAB to perform nonlinear regression analysis on equation (3.2). Regarding the regression analysis of the emission model, the relatively large number of coefficients warrant the assumption that even physically–chemically nonsensical values may result in a fit for multiple value combinations and that random initial values may cause local minima that the iteration of the coefficients won't be able to traverse while looking for the minimum value. This means that even of the function is convergent, it may not reach the global maximum. From this consideration, fitting the emission models was preceded by determining the initial values of the coefficients based on the analysis of their measured values.

The lower envelope and the asymptote of the upper envelope of the emission model (equation 3.2) are obtained as the limit values of the sinusoidal function described by equation (3.2) fitted to the measurement data of the untilled area.

$$W_{ref} = b_1 + b_2 \sin\left(\frac{2\pi}{b_3} t - b_4\right) \tag{3.3.}$$

where W_{ref} a is the emission intensity of the untilled area $\left[\frac{g}{m^2 h}\right]$, b_1 is the mean emission coefficient, b_2 is the coefficient of the emission amplitude $\left[\frac{g}{m^2 h}\right]$, b_3 is the coefficient of the emission cycle time, b_4 is the coefficient of the emission phase shift, and t is time $[h]$.

The coefficients of equation (3.3) were determined using the least squares method as follows:

$$min\left\{\sum_{t_0}^{t_{end}} \left(W_{ref}(b_1, b_2, b_3, b_4) - W_{ref_{mért}}\right)^2\right\} \tag{3.4.}$$

where $W_{ref} =$ is the CO2 emission intensity of the untilled area, $W_{ref_{mért}}$ is the CO2 emission of the reference area as determined by measurements $\left[\frac{g}{m^2h}\right]$, $b_1, b_2, b_3, b_4 =$ the coefficients of equation (3.2.).

After having determined the limit values for the envelope curves of the emission model, I fitted the entire quantitative model by minimizing the differences of the elementary numerical integrals as follows:

$$\int_{t_0}^{t_{end}} |W_{mért} - W(c_0, c_2, A)|dt \to min \tag{3.5.}$$

where W is the CO2 emission function of the soil, $W_{mért}$ is the CO2 emission of the tilled area $\left[\frac{g}{m^2h}\right]$, and $c_0, c_2, A =$ the coefficients of equation (3.2.).

3.5. The results of emission model fitting

Figure 3.11 through Figure 3.14 show the fitting of the emission model to the values of the tilled area as well as the exponential envelope curves.

Table 3.3 shows the accuracy of fitting the sinusoidal model member to the measured values of the untilled area, the accuracy of fitting the emission model to the values of the tilled area, and the emission values determined from measured and calculated data.

The nonlinear regression analysis of the presented model for the studies performed under the defined conditions resulted in the emission coefficients summarized in Table 3.4.

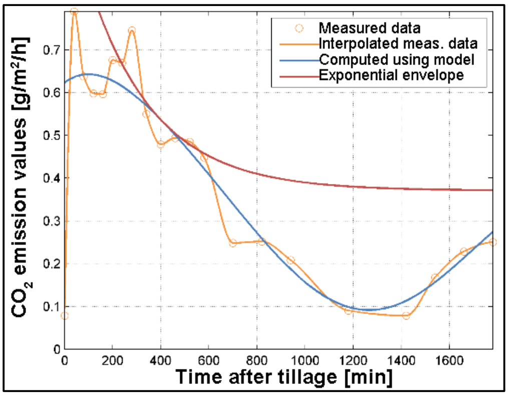


Figure 3.11 Emission model fitted to the data of ploughed area (Measurement 9)

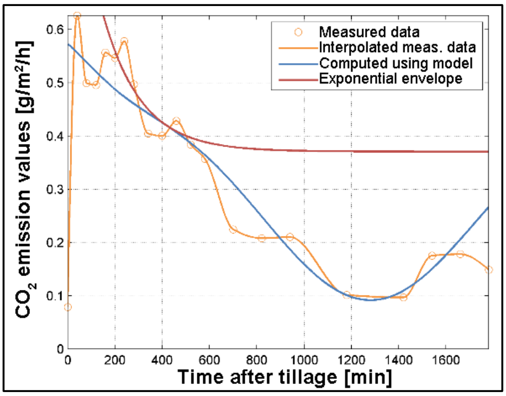


Figure 3.12 Emission model fitted to the data of disked area (Measurement 9)

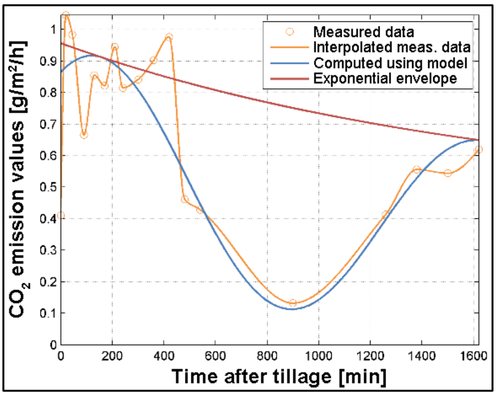


Figure 3.13 Emission model fitted to the data of ploughed area (Measurement 10)

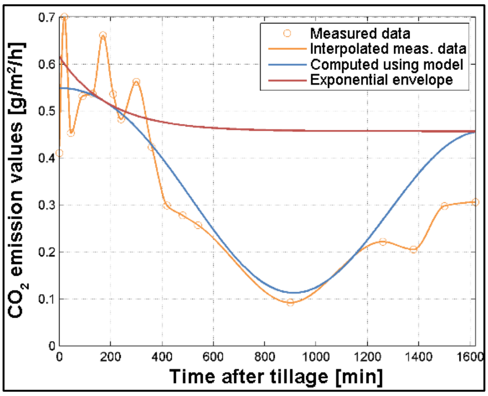


Figure 3.14 Emission model fitted to the dataof cultivated area (Measurement 10)

Table 3.3 The fit of the emission model on the measured data, and the CO_2 quantity emitted during the measurement

	Determining coefficient (R^2) [%]	**CO_2 emitted according to measured data [g/m²]**	**CO_2 emitted according to model data [g/m²]**	**Deviation of CO_2 emission from that of the untilled area**	
				[g/m²]	**[%]**
Measurement 9					
Reference	72.58	6.876	6.875	-	100
Ploughing	93.26	9.380	9.267	2.392	134
Disking	88.86	8.162	7.883	1.008	114
Measurement 10					
Reference	81.10	8.074	8.074	-	100
Ploughing	77.99	13.044	13.467	5.393	166
Field cultivating	88.86	8.509	7.603	-0.471	94

Table 3.4 Coefficient values of the fitted emission model for the tilled areas

	A	**c_0**	**c_1**	**c_2**	**h**	**j**
Measurement 9						
Ploughed Area	0.6991	-0.0036	0.0037	-0.0870	0.2791	0.0917
Disked Area	0.6507	-0.0062		-0.0353		
Measurement 10						
Ploughed Area	0.4994	-0.000058	0.0043	-0.8985	0,3443	0,1127
Disked Area	0.1589	-0.0052		-0.8234		

The results presented above justify the statement that the applied emission model approximates the measured values to the degree that can be expected for the CO_2 emission of tilled soils.

3.6. Development of the emission model

The sinusoidal member of the emission mode used for approximating the measurement results takes into account the temperature dependence of soil CO_2 emission based on the trigonometric nature of temperature variance. This representation of the temperature variance in the emission model is covered by the linear function between temperature and CO_2 emission. Due to its quantitative nature, the method provides sufficiently accurate results for the amounts of CO_2 emitted after tillage, as the regression analysis of the whole model relies on a step by step minimization of the numeric integrals. The method presented provides a good approximation of the emitted amount of CO_2, specified as a research goal and the most important factor of climate change, and does so with the help of regression analysis that can be performed using a relatively simple algorithm. Also, the model can be modified if the goal is to describe the trajectory of the emission function. The emission model can be complemented by temperature vs. CO_2 emission models for untilled soils as can be found in literature (FANG and MONCRIEFF, 2001; LELLEI-KOVÁCS, 2011). Doing so would change the sinusoidal periodic trajectory of the model, providing a more accurate description of the temperature dependence of emissions using a modified sinusoidal function. A theoretical extension of the model along these lines could be important especially for describing the CO_2 emission of untilled areas used as reference for measurements, since results obtained from medium-duration tests indicate that emission curve trajectories for tilled areas are primarily dominated by enzyme-kinetic laws, especially in the case of intensive tillage.

In order to explore differences between the qualitative and the quantitative approach, I have compared the linear function relationship used (equation 3.6) with the O'Connell model (equation 3.7) found by (LELLEI-KOVÁCS, 2011) to provide the best approximation. The description of this model reflects the biochemical foundations to a lesser degree but, according to (LELLEI-KOVÁCS, 2011), it gives a similar or, in certain cases, better approximation than for instance the Lloyd–Taylor model based on the Arrhenius relationship, and is also easier to handle mathematically.

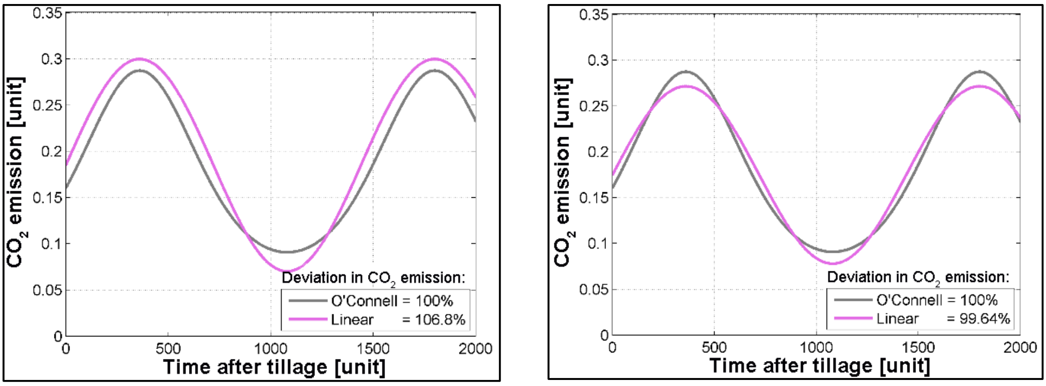
$$Y = a + bT \,, \tag{3.6.}$$

where Y is the CO_2 emission $[\frac{g}{m^2 h}]$, T is the temperature [^{o}C], a = 0.143 is the model parameter for field soils [-], and b = 0.0164 is the model parameter for field soils [-] (FANG and MONCRIEFF, 2001).

$$Y = ae^{(bT+cT^2)} \,, \tag{3.7.}$$

where Y is the CO_2 emission $[\frac{g}{m^2 h}]$, T is the temperature [^{o}C], a = 0.03282, and b = 0.07640, and c = $1.485*10^{-4}$ are model parameters for farm soils (FANG and MONCRIEFF, 2001).

Figure 3.15 shows the difference between the O'Connell model and the linear model. The figure shows that using the coefficients determined by FANG and MONCRIEFF, (2001), the tracking of the two curves is unsatisfactory, as is the deviation of the numeric integrals. The linear model provides a relatively poor approximation of the O'Connell model because FANG and MONCRIEFF (2001) determined their coefficients to approximate the measured data rather than fitting them to a universal relationship model (that does not as yet exist). This is the reason for the deviation shown in Figure 3.15/a when using the coefficients provided. If the coefficients of the linear relationship model are determined by a regression analysis of the values of the O'Connell model, the emitted quantity computed using the model does not exhibit a significant deviation, only curve trajectories are slightly different (Figure 3.15/b).



a) b)

Figure 3.15 Shapes of different emission models

a) using the coefficients determined by Fang and Moncrieff (2001)

b) using the coefficients determined by fitting the linear model

Based on this, the linear relationship between the temperature function and the emission function as applied in the proposed practical model does not introduce any inaccuracy or neglect anything significant since the model coefficients are obtained by approximating the measured points. The deviation presented becomes even less important for tilled plots due to the predominance of the enzyme-kinetic effect that is the primary factor in determining the shape of the emission curve until the envelope reaches the neighborhood of the asymptote, i.e. the maximum value of the untilled area, with a value corresponding to the measurement accuracy. The emission of the untilled reference area is almost exclusively determined by the temperature dependence of the enzyme reactions. Hence the temperature vs. emission relationship models should be taken into account for the reference area. Accordingly, when using the O'Connor model to approximate the measured data of the untilled area, the daily temperature variance function of equation (2.3) should be substituted in the O'Connell model. This yielded the following model for studying the fit of the data obtained from medium-duration measurements:

$$W_r = a\, e^{\left(b\,[\mathrm{k}+l\sin(c_1 t)]+c[\mathrm{k}+l\sin(c_1 t)]^2\right)}\,, \tag{3.8.}$$

where W_r is the CO2 emission $[\frac{g}{m^2 h}]$, $a = 0.03282$ is a model parameter [-] (FANG & MONCRIEFF, 2001), $b = 0.07640$ is a model parameter [-] (FANG & MONCRIEFF, 2001), $c = 1.485{*}10^{-4}$ is a model parameter [-] (FANG & MONCRIEFF, 2001), k is the coefficient of the median temperature [-], l is the coefficient of the temperature amplitude [-], c_1 is the emission period [-], and t is the time [min].

The results of model fitting are presented in Figure 3.16 and Figure 3.17. As shown in the figures, the emission model complemented by the O’Connell model yields a better fit because of the higher value of the coefficient of determination in Measurement 9, but Measurement 10 shows the opposite, which means that the value of the coefficient of determination has decreased, if only to a much smaller degree. Note, however, that the amount of CO_2 emitted on the reference areas during measurements showed only a negligible deviation between results obtained with the earlier model and those obtained when complementing it with the O’Connell relationship model (Table 3.5).

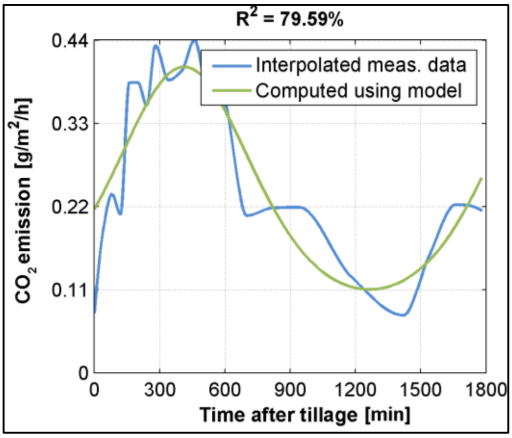


Figure 3.16 Fit of the sinusoidal member of the complemented emission model (Measurement 9)

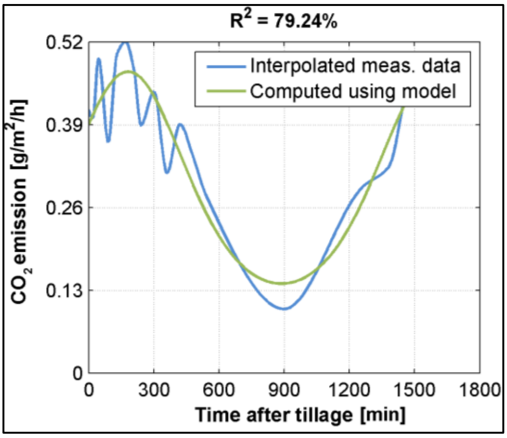


Figure 3.17 Fit of the sinusoidal member of the complemented emission model (Measurement 10)

Table 3.5 Results of fitting the complemented emission models

	Untilled area (Meas. 9)	**Untilled area (Meas. 10)**
Coefficient of determination (R^2) [%]	79.59	79.24
Quantity [g/m^2] of emitted CO_2 based on interpolated data	6.876	8.074
Quantity [g/m^2] of emitted CO_2 based on the linear model	6.875	8.074
Quantity [g/m^2] of emitted CO_2 based on the O’Connell model	6.859	8.096
Deviation between O’Connell model and the linear model	99.76	100.2

In order to better present the shape of the emission function of reference areas and to facilitate the comparison with data found in the literature, reference areas are best studied using the O’Connell model or other soil temperature vs. CO_2 emission relationship models.

4. NEW SCIENTIFIC RESULTS

1. I have developed a new procedure for measuring the soil emission effects of different tillage methods. The main components of the new procedure are as follows:
   - In order to ensure measurement accuracy, the part of the incubation chambers above soil level must be isolated from the ambient air because measurement experiences show that insufficient environmental isolation introduces significant errors.
   - Measurement cycle times must be minimized for an accurate description of the emission process. This should be based on the instrument's required measurement time and the number of sampling areas.
   - The measurement chambers must be placed at different measurement points for each measurement cycle to represent soil heterogeneity. The measurement chambers must be ventilated between measurements.
   - Measurements must be performed with minimized incubation times due to the adverse effect of chamber isolation on the soil's microclimate.
   - The optimal incubation time can be determined based on the size of the measurement chamber and the measuring and reading accuracy of the instrument.

2. I have developed a soil CO_2 emission model that uses first-order reaction-kinetic laws to account for changes in soil surface emission intensity caused during tillage by the catalyzing effect of air mixed with soil, and also accounts for the temperature dependence of biochemical processes by factoring in the nature of soil temperature changes and the relationship between soil temperature and CO_2 emission.

   I have proved that after tillage, the overall CO_2 emission can be described using a sinusoidal function with exponentially damped amplitude, and that under the study conditions, the upper envelope of this function can be approximated with an exponential function while its lower envelope is a constant function corresponding to the minimum emission value of the untilled area.

   I have found that in the general case, both the upper and the lower envelope curve of the model has a sinusoidal periodicity and an exponentially decreasing amplitude.

3. Based on the emission model developed, I have formulated the following new relationship for the change in CO_2 emission after tillage:

$$W = \left(\left(\frac{\left(Ae^{(t \cdot c_0)}\right) + h}{2} \right) \left(\sin(c_1\, t - c_2) + 1\right) \right) + j.$$

I have proved that using this new relationship, soil CO_2 emission after tillage can be determined up to the point in time when the exponential envelope curve approaches the asymptote within the specified measurement accuracy. The formula uses the following parameters: initial emission value (A), envelope gradient (c_0), maximum (h) and minimum (j) reference emission, emission period (c_1) and phase shift (c_2), and time elapsed since tillage (t).

I have found that for studies performed under the defined conditions on sandy soil with low organic content, the emission coefficients of the formula introduced above are as follows:

	A	c_0	c_1	c_2	h	j
Ploughed Area	0.6991	-0.0036	0.0037	-0.0870	0.2791	0.0917
Disked Area	0.6507	-0.0062		-0.0353		

I have found that for studies performed under the defined conditions on heavy loamy clay soil with low organic content, the emission coefficients of the formula introduced above are as follows:

	A	c_0	c_1	c_2	h	j
Ploughed Area	0.4994	-0.000058	0.0043	-0.8985	0.3443	0.1127
Cultivated Area	0.1589	-0.0052		-0.8234		

4. The emission model I have developed shows a sinusoidal relationship for undisturbed soil when $T \to \infty$. I have developed the following formula for a more accurate description of emission for the period when the catalyzing effect of tillage has decayed:

$$W_r = ae^{\left(b[\mathrm{k}+l\sin(c_1 t)]+c[\mathrm{k}+l\sin(c_1 t)]^2\right)}.$$

Based on the literature, this relationship takes into account the relationship models for soil temperature vs. CO_2 emission and can be used to compute emission intensity using model parameters *a, b, c*, the median temperature coefficient (k), the temperature amplitude coefficient (l), the emission period (c1) and the time elapsed since tillage (t).

5. I have developed a new algorithm for studying the effect of different tillage machines on CO_2 emission; the algorithm can be used to fit the CO_2 emission model after different types of tillage and to determine the model coefficients. In the first step of the algorithm, field measurements are performed on untilled areas and areas tilled using different methods. In the second step, the model member for the untilled area is fitted in order to determine the maximum and minimum reference emission and the cycle time. In the third step, the entire emission model is fitted in order to determine the coefficients that define the initial value of emission, the gradient of the envelope curve, and the phase shift of the emission.

6. I have determined the amount of CO_2 emission for ploughing, disking, and field cultivation, and have found that ploughing has the most adverse effect on climate change.

   I have determined that while measurements with a cycle time of 2–5 hours are suitable for ranking the different tillage methods, they can not be used to determine the amount of CO_2 emitted.

5. CONCLUSIONS AND RECOMMENDATIONS

Approximation models developed by earlier research did not provide an accurate description of the emission curve. In my view, one of the main reasons is the fact that the procedures they used for field measurements were complex as well as capital- and logistics-intensive. This resulted in relatively long sampling cycle times, making it impossible the more accurately analyze the shape of the emission curves. The measurement procedure I have developed and validated does not significantly differ from the procedures used by Hungarian researchers and can be used to investigate the CO_2 emissions of different tillage methods with the cycle time and accuracy required for accurate modeling by adhering to the critical conditions formulated based on measurement experiences.

With appropriate measured data, the procedure described in the Results can be used to fit the emission model and to determine the quantitative CO_2 emissions of further tillage methods. My results can be used to develop new low-emission procedures and machines, whose environmental impact could be measured and their use may be subsidized.

The most important conclusion of the results outlined above is that it is feasible to model the CO_2 emission of tilled soils while taking into account the physical and biochemical action principles that form the foundation of the emission phenomenon. The emitted quantity can be determined numerically with the expectable accuracy, especially useful when comparing different tillage methods.

The developed emission model and the algorithm of the regression analysis needed to fit it are suitable for modeling not only the tillage methods I have investigated but also other tillage methods currently in use or, in fact, all tillage methods. While the measurements that the performed regression analysis relied on were performed under different conditions, these conditions can by no means be considered extreme in terms of the state of the soil. This makes it necessary to study the statistical reliability of the model also under unfavorable soil conditions. In addition, further measurements and model fitting can be used to study the effects of different soil and tillage parameters. If measurement data in sufficient quantity and variability are available, factor analysis can be used to determine the direct effects of the different model-independent parameters (soil type, humidity, temperature, etc.) on CO_2 emission after tillage. The cross impacts of the different parameters can also be studied if a sufficient amount of measurement data is available.

The single most important limit to the usability of my emission model is the effect of fast-changing environmental parameters. Hence, further work is needed to study the effects of sudden changes in temperature, atmospheric pressure, wind speed, and precipitation. Studies of the direct effects of these phenomena are necessary for the general usability of the model.

6. SUMMARY

Industrial activities during the past 150 years have increased the concentration of atmospheric greenhouse gases to a level that has caused the annual average temperature to rise at an accelerating pace. This change has been brought about primarily by energy generation, the industry, intensive agriculture, and forestry. In addition to the intensive emitters, tillage must also make its contribution to mitigating and reversing climate change. Decreasing the CO_2 emission of tilled soils as part of the mitigation of the primary impacts on climate change also serves to protect the carbon stock and increase the soil's organic content, ultimately improving soil quality.

While good estimates are available for the overall CO_2 emission of tilled soils, there is still a lack of knowledge about how to model the CO_2 emissions of different tillage methods and accurately determine the effects of different tillage methods and systems on soil CO_2 emission.

My research goals included developing a measurement procedure to determine the CO_2 emission of tillage methods, determining the change in soil CO_2 emission after tillage by measurements, and describing the post-tillage emissions of tilled areas using the measured data and a mathematical model.

In order to achieve these goals, I have reviewed the literature of measurement methods used earlier, and I have developed a study method that is based on a simple measurement principle and can be used in practice. I have developed and validated the measurement procedure by field measurements.

I used this new measurement procedure to perform short and medium duration measurements on multiple test sites, including untilled fields and fields cultivated with various tillage machines, in order to determine the CO_2 emission of the soil after tillage.

Using the environmental and biochemical relationships that determine the CO_2 emission of freshly tilled soil, I developed a generalized emission model that can also be applied to the measurements performed, as well as the algorithm needed to fit the model. Using the developed algorithm, regression analysis, and the measured data, I validated the emission model and determined its coefficients as well as the amount of CO_2 emitted.

Based on the results of this research work, I formulated new scientific results that can be used to determine the effects of different tillage methods on the CO_2 emission of the soil.

7. ESSENTIAL PUBLICATIONS PERTINENT TO THE TOPIC OF THE DISSERTATION

Proofed foreign language articles

Rádics, J.P., Jóri, J.I. (2012): State of the art in the Hungarian field research: the effect of tillage on CO_2 emission. Hungarian Agricultural Engineering, Vol. 24. pp. 43–48. ISSN 0864-7410

Rádics, J.P., Jóri, J.I., Fenyvesi, L. (2014): Short-term study of tillage induced soil CO_2 loss. International Journal of Innovative Research In Advanced Engineering, Vol. 1. (12) pp. 48–52. ISSN 2349-2163

Rádics, J.P., Jóri, J.I., Fenyvesi, L. (2014): Soil CO_2 emission induced by tillage machines. International Journal of Applied Science and Technology, Vol. 4. (7) pp. 37-44. ISSN 2221-0997

Rádics, J.P., Jóri, J.I., Fenyvesi, L. (2014): Field study of soil CO_2 emission to investigate environment-friendly effect of different tillage practices. The Experiment – International Journal of Science and Technology, Vol. 28. (3) pp. 1915-1922. ISSN 2319-2119

Rádics, J.P., Jóri, J.I., Fenyvesi, L. (2015): Intelligent tillage machines development to mitigate climate change effects. Journal of International Scientific Publications Agriculture & Food, Vol. 3. (1) pp. 1-11. ISSN 1314-8591

Proofed Hungarian articles

Rádics J.P., Jóri J.I. (2008): Intelligens talajművelőgépek fejlesztésének követelményrendszere. GÉP, LIX. évf. (4) 38–42. o. ISSN 0016-8572

Rádics J.P., Jóri J.I., Fenyvesi L. (2015): Talaj CO_2 kibocsátási modell validálása nemlineáris regresszió analízissel. GÉP, LXVI. évf. (1) 5-9. o. ISSN 0016-8572

Rádics J.P., Jóri J.I., Fenyvesi L. (2015): Talajművelő gépek hatása a talaj szén-dioxid kibocsátására. Mezőgazdasági Technika, LVI. évf. (2.) 2-5. o. ISSN 0026 1890