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SOIL RESPIRATION AND SOIL WATER REGIME IN DIFFERENT LAND MANAGEMENT SYSTEMS

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Abstract
Soil carbon and water dynamics are relevant indicators of soil functioning, especially from the agricultural perspective. However, any human interventions, especially tillage, affect physical and hydraulic properties of soil and hence soil carbon dynamics through soil water content. In this paper we aim at the determination of short term and long term effects of soil tillage on soil respiration soil water content (SWC) and soil temperature regime. The study site is located in Hungary, near city Hatvan in a long-term tillage treatment experiment. Soil respiration, soil water content and soil temperature were monitored in the direct drilling (no-till) and ploughing tillage systems. Results showed that although no-till emissions are higher in most of the measurement days, tillage treatment does not affect CO_2 emission significantly in the investigated period as a whole. There are however, significant differences on particular measurement days. Soil moisture and soil temperature were examined using the HYDRUS mathematical model to better understand the underlying processes. The simulations agreed well measured SWC (*RMSE* = 0.0311 m^3 m^{-3} and 0.0351 m^3 m^{-3}), but further model calibration is required before simulating CO_2 efflux.

1. Introduction
In agricultural settings, different tillage applications have been used widely to enhance crop yield and growth. Different tillage applications have great effect on soil structure, therefore on soil water –and heat regime as well. Many studies reported that soil conserving tillage practice as no till or direct drilling results higher water content in the soil profile (Gauer et al., 1982, Mielke et al., 1986, Radford et al., 1995) comparing to conventional tillage application as plowing (Schwartz et al., 2010). Soil temperature is also influenced by tillage, the upper layer of the soil warms up easier when the structure is homogenized and porous (Hay et al., 2006). Both soil water content and soil temperature are the main driving factors in soil carbon-dioxide (CO_2) emission because they directly affect roots and microbial functioning (Smith et al. 2003; Szili-Kovács 2004, Subke & Bahn, 2010). Consequently different tillage applications can significantly influence soil respiration rate (Tóth & Koós, 2006, Tóth [illegible] understand the [illegible] nt regimes can be simulated by process-based dynamic models such as SWAP, HYDRUS, COUP etc. (Farkas et al., 2014; Horel et al., 2014).

Although the effect of different tillage treatments on soil water and heat or carbon-dioxide regime is well established, there are only a limited number of studies where the tillage effect on all these three processes have evaluated with mathematical modelling. We used the Hydrus 1D mathematical model to evaluate the effect of direct drilling (NT) and ploughing (P) tillage treatments.

2. Materials and Methods

2.1 Study sites and soil parameters

Field investigations were carried out in a tillage treatment experiment in 2014. The trial was established in 2002 on a loamy chernozem soil at the experimental site of the Szent István University nearby the city Hatvan, northern Hungary. The annual average precipitation is 580 mm (662 mm in 2014), 323 mm of that falls in the vegetation period. Every tillage treatments have been applied in 4 replicates in randomized striped design. The area of each plots is 975 m^2. Before sowing sunflower in the 14th of April in 2014, the last tillage operation was applied in the 18th of October, 2013.
The studied tillage treatments with the main tillage depth and some general soil characteristics (pH, organic carbon -and humus content) of the upper 10 cm and some microbial characteristic (WEOC, WEN, microbial biomass C – and N) of the upper 5 cm are reported in Table 1.

Table 1. Soil characteristics at the study site.

Tillage treatment	Tillage depth	pH(H_2O)	pH(KCl)	Organic C	Humus content	WEOC	WEN	microbial biomass C	microbial biomass N
	cm			%	%	µg C g-1 soil	µg C g-1 soil	µg C g^{-1} soil	µg C g-1 soil
Ploughing (P)	26-30	7.13	5.81	1.94	3.34	47.03	51.54	19.5	3.8
Direct drilling (DD)	-	6.44	5.06	2.30	3.97	73.33	63.42	39.9	7.1

On the base of soil characteristics influencing directly the microbiological activity such as microbial biomass carbon and nitrogen content a significant difference can be seen between the studied treatments. It can be explained with the higher humus and organic carbon content in the direct drilling treatment and with the undisturbed circumstances which ensure favorable environment for the microbes.

2.2 Field measurements and instrumentation

Soil water content and soil temperature were measured with 5TM Decagon probes at five soil depth (5-10, 15-20, 30-35, 40-45, 65-70cm) in both studied treatments. Each probes were calibrated in laboratory for the soil of that treatment where the probes were settled later. For the calibration the 0-30 cm and the 30-70cm layer was used separately for the upper two and the lower three probes. Soil water content data measured during 2014 were adjusted based on the calibration equations. Soil water content and temperature measurements were taken from the beginning of the year till the tillage operation on October 2 when all the probes were removed.
Soil carbon-dioxide (CO_2) emissions were measured with closed chamber technique once per week in the vegetation period in the two treatments. Measurements were performed in seven spatial replicates with chambers laced in a randomized pattern close to the center of each treatment stripe. Air samples were collected using air-tight 100 mL syringes (Hamilton GASTIGHT syringes) and were analyzed in the laboratory later to estimate CO_2 concentrations using gas-chromatograph with flame ionization detector (GC). GC-FID analysis was performed using a GC 8000 (Fisions Instruments) with column parameters: 2 m by 3 mm. The method used a splitless injection with hydrogen carrier gas (pressure: 90 kPa; flow: 30 mL min^{-1}). The oven temperature was kept constant at 80 °C for the duration of 180 s. Calibration standards of 1000 mg kg^{-1} CO_2 were run after each sample runs, containing approximately 30 samples.
Differences in CO_2 emissions were evaluated using Mann-Whitney test. The statistical significance was defined as $p < 0.05$.

Daily precipitation totals, daily minimum and maximum temperatures were measured at a nearby meteorological station (Aszód), about 6 km southwest from the study site. Further meteorological parameters such as vapor pressure deficit was estimated using the MT-CLIM mountain climate simulator (version 4.3 Numerical Terradynamic Simulation Group, University of Montana Thornton & Running, 1999) based on the previous meteorological variables and site-specific parameters.

2.5 Numerical modeling

Water and temperature regimes were simulated in the period between January 1 and December 31, 2014. In the model simulation, time 0 corresponds to January 1. The one-dimensional flow domain was set to a depth of 70 cm and divided into three dual porosity layers, 0–30, 30–45, and 45–70 cm.
The Hydrus-1D code (Simunek et al., 1998; 2007) with dual-porosity (Durner, dual van Genuchten-Mualem) soil hydraulic model was used to simulate one-dimensional vertical water and heat flow under field conditions. The dual-porosity model was used to simulate water flow within the soil profile with no hysteresis in the hydraulic model.
Root water uptake was simulated using S-Shape reduction model (van Genuchten, 1985). Root and plant growth or leaf area index (LAI) data was calculated by interpolating weekly measured data and was added to the model.

2.5.1 Model description – water flow

The Hydrus-1D code numerically solves the Richards equation for variably saturated water flow (Barry et al. 1993):

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z} \quad K \ \theta \ \frac{\partial\theta}{\partial t} + K \ \theta \qquad (1)$$

where *z* (cm) is the vertical space coordinate positive upward and *t* is time (d).

Table 2 summarizes the soil hydraulic parameters for the dual-porosity soil matrix. θ_r and θ_s are the residual and saturated water contents, respectively, α and *n* are fitting parameters, K_s is the effective hydraulic conductivity, *I* is the tortuosity parameter in the conductivity function [-], and *w2* represent the relative weighting factor for the subcurve of the second overlapping subregion. Soil profile consisted of 3 layers (Table 2).

Table 2. Estimated soil hydraulic properties for ploughed soil profiles.

Depth (cm)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	*n* (–)	K_s (cm d^{-1})	*I* (–)	*w2* (–)	α2 (cm^{-1})	*n2* (–)
0-15	0.07	0.50	0.28	1.21	150	-1	0.10	0.20	1.15
15-25	0.06	0.48	0.20	1.16	30	-1	0.10	0.03	1.50
25-70	0.06	0.45	0.05	1.16	0.90	-1	0.10	0.03	1.50

3.5.2. Model description – heat transport

The Chung and Horton (1987) thermal conductivity equation was used to simulate heat transport:

$$\lambda_0 = b_1 + b_2\theta + b_3\theta^{0.5} \qquad (2)$$

where b_1, b_2, and b_3 are empirical parameters.

3.5.3. Initial (IC) and boundary conditions (BC)

An atmospheric boundary condition was imposed at the soil surface accounting for time-dependent data of precipitation (cm d^{-1}), potential evaporation rate (cm d^{-1}) and minimum allowed pressure head (cm).

The potential evaporation (E_p; cm d^{-1}) was estimated from Penman-Monteith combination equation (Monteith, 1965, 1981). A free drainage condition was used at the bottom boundary (z = 70 cm) of the flow domain. The value of the h_S (maximum head pressure) was set to 3, whereas h_A was set to 100 m. For the heat transport boundary conditions temperature upper BC and zero gradient lower BC was assumed.

The evaluation of the simulated results was done by graphically by plotting the modeled and measured data, and statistically by calculating the root mean square error (*RMSE*).

$$RMSE = \left[\frac{\sum_{i=1}^{n} p_i - m_i}{n} \times \frac{1}{m}\right]^{0.5} \qquad (3)$$

where p_i are the predicted values, m_i are the measured values, m is the average value of observed data and n is the number of observations.

3. Results and discussion

3.1 CO_2 emission from different tillage systems

Soil CO_2 efflux showed a clear annual course in 2014 regardless of tillage treatment (Fig. 1.). Soil temperature (ST) is known to be a major driver of soil respiration should be considered as a cause for this phenomenon. In the investigated period CO_2 efflux measured in the NT treatment exceeded that in the P treatment on 21 measurement days out of 32 occasions when data in both treatments were available. However, statistical analyses revealed that throughout the year, CO_2 emissions do not differ significantly in the NT and P treatments (Figure 1). Only six measurements showed significant differences between treatments ($p < 0.05$), among which, NT emissions were higher in four and P emissions were higher in 2 cases (24. 04. 2014 and 28. 10. 2014). These two cases was preceded by disturbance events, namely sowing (14. 04. 2014) and autumn tillage (conventional ploughing; 2014. 10. 02), respectively.

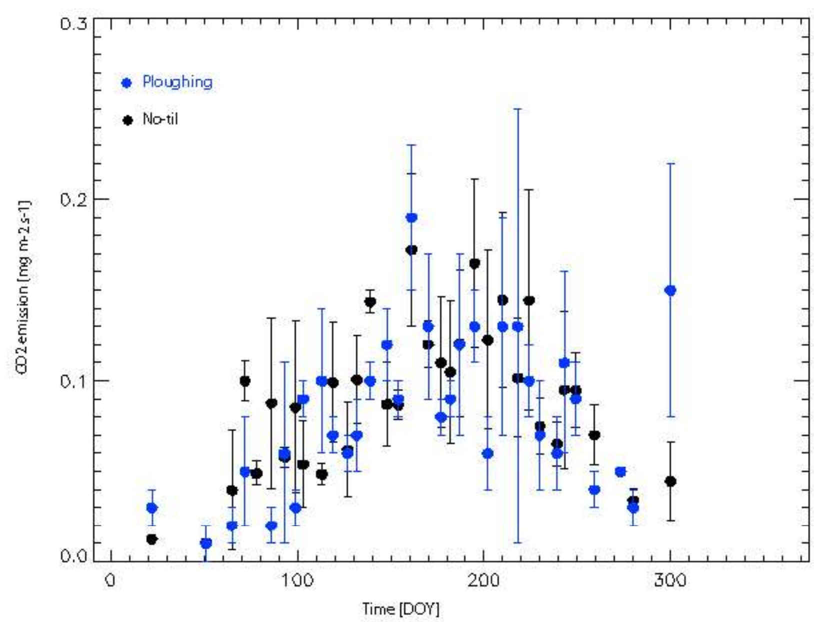

Figure 1. Soil CO_2 emissions in 2014 in no-till (NT) and ploughing (P) treatments.

3.2 Effect of tillage systems on soil water and temperature regime

We examined variations of soil temperature and soil water content as main drivers of soil respiration, and made a first attempt to simulate their courses throughout the year.
Infiltration rates through the ploughed and no till soil columns were estimated using a single ring infiltrometer at 0.5 and 2.0 cm suctions. Based on 10.5 minutes averages, the ploughed soil layer had approximately 2.4 and 2.6 times higher infiltration rates compared to no till system at 0.5 and 2.0 cm suctions, respectively.

4.2.1. Soil temperature changes with depth
The change in temperature at different depths are shown in Figures 2a and 2b. Even though the sensitivity to the air temperature changes decreases with depth, in both cultivation systems the soil layers at a given depth follow an almost identical temperature change tendency. Therefore, in the present study, the cultivation systems did not affected soil temperature changes considerably.

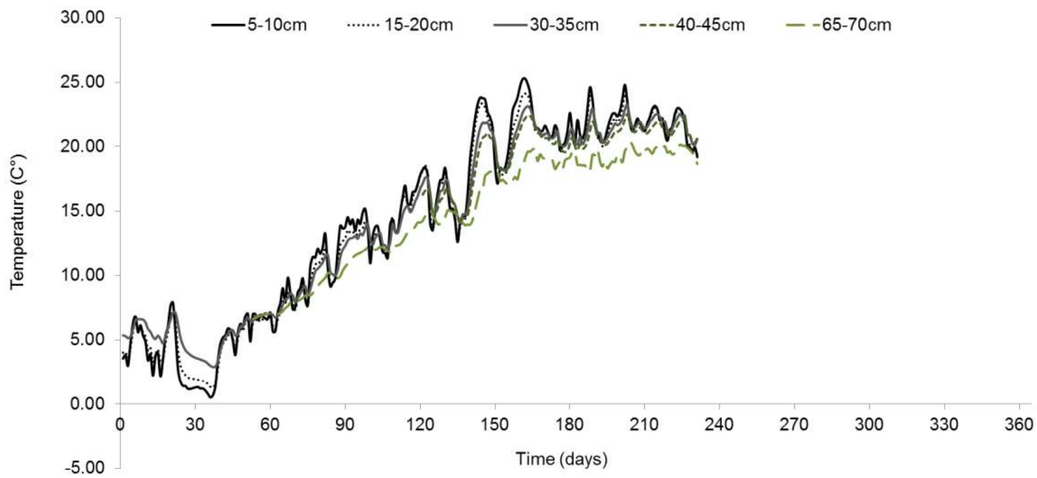

Figure 2a. Daily average soil temperatures (Celsius) at different depths under ploughing cultivation method.

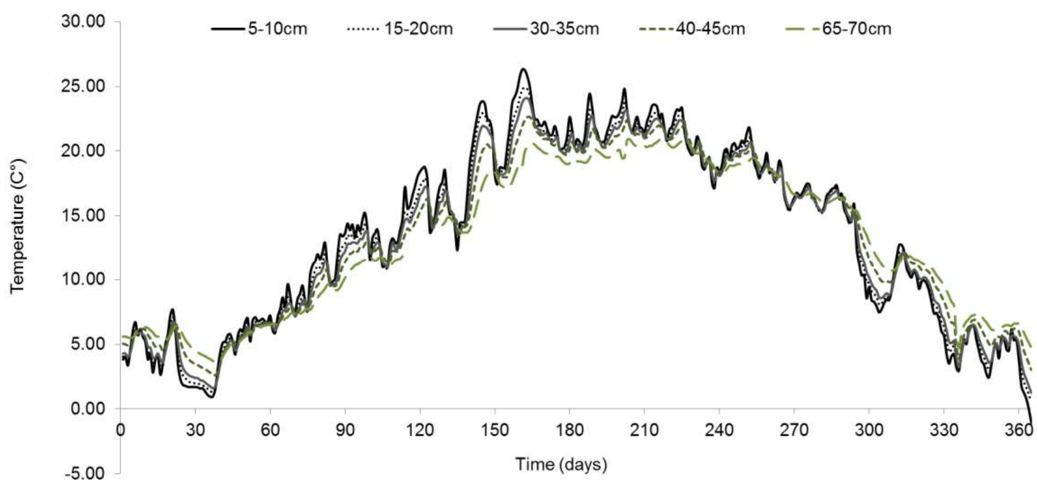

Figure 2b. Daily average soil temperatures (Celsius) at different depths under no tillage cultivation method.

4.2.2. Soil water changes in the different cultivation systems

Soil water content was significantly different between the two treatments ($p < 0.01$, Mann-Whitney test). To reveal the possible causes, we performed numerical simulations of water movement in the soil profile. The main difference between ploughed and no tilled soil management system was assumed in soil hydraulic properties, especially in the hydraulic conductivity values. While ploughed system upper soil layer had K_s = 150 cm/d, the no tillage system K_s value was set to be 100 cm/d. Based on the above mentioned parameters both the simulated and measured values are presented on Figures 3-6.

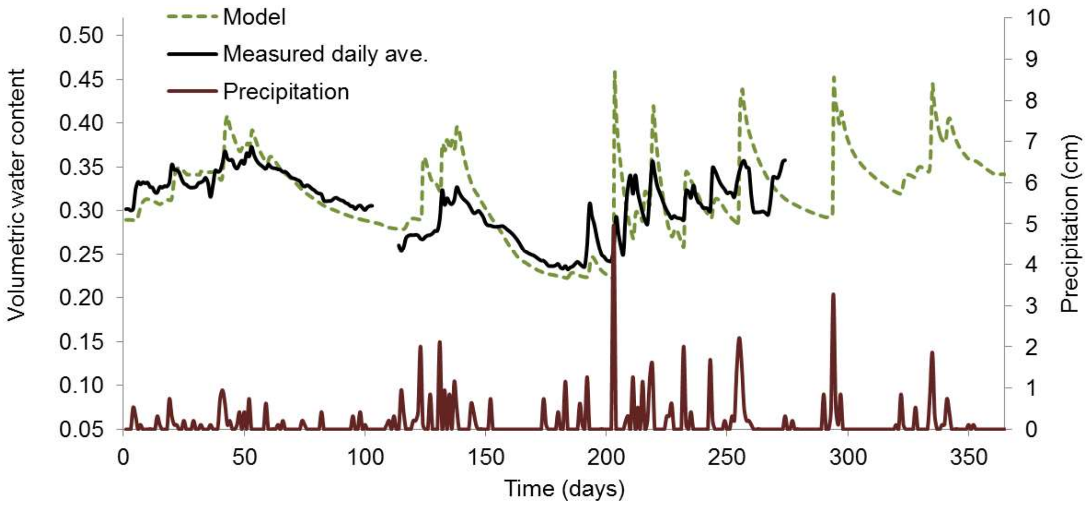

Figure 3. Average measured and simulated soil water content (VWC) at 20-25 cm below the ploughed soil column.

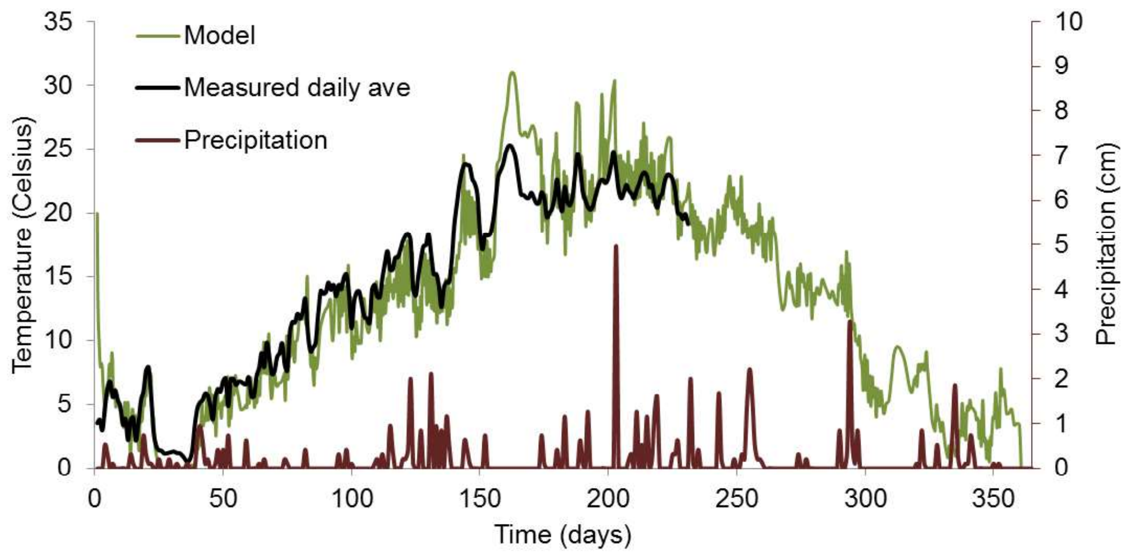

Figure 4. Average measured and simulated soil temperature at 20-25 cm below the ploughed soil column.

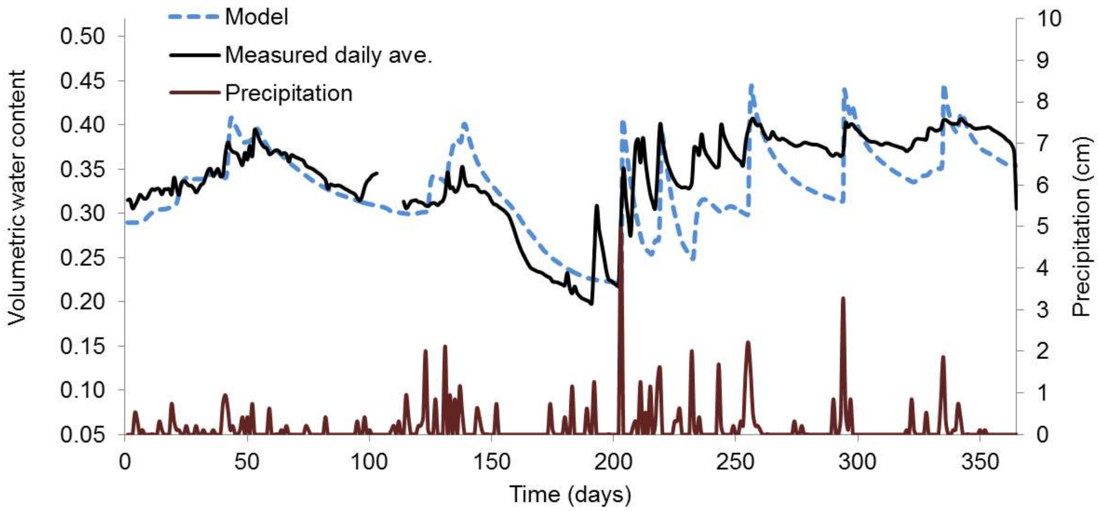

Figure 5. Average measured and simulated soil water content (VWC) at 20-25 cm below the no tilled soil column.

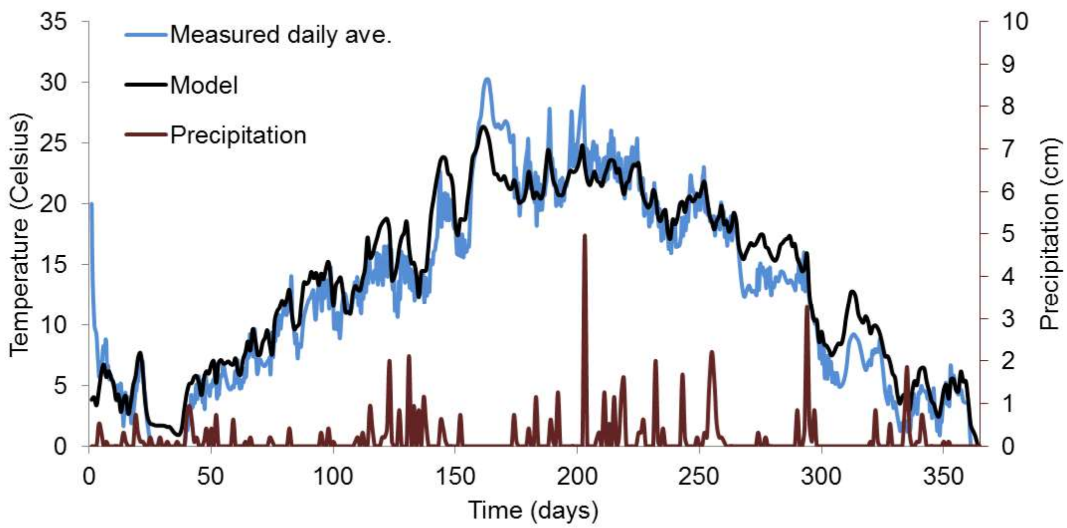

Figure 6. Average measured and simulated soil temperature at 20-25 cm below the no tilled soil column.

Model errors associated with the different cultivation systems compared to measured data were very similar in both data sets, *RMSE* = 0.0311 m^3 m^{-3} and 0.0351 m^3 m^{-3} for ploughed and NT, respectively. During the first half of the year, soil water changes aligned relatively well in both cultivation systems with *RMSE* = 0.0288 and 0.0273 for ploughed and NT, respectively. During the second part of the year, the model inaccuracies become more pronounced, almost doubling the error values (*RMSE* = 0.0410 and 0.0445 for ploughed and NT soils, respectively). The second part of the year, the sunflower root systems might take up less water and also could have less evapotranspiration values as we estimated, which could result in a more sudden changes in soil water contents in the model (Figures 3 and 5).

Measured and simulated SWC and soil temperature courses agreed well, however, further optimization should be carried out before any attempt to simulate CO_2 emissions using the model.

4. Conclusions

Soil CO_2 efflux measurements supported our hypothesis that emissions are higher in no-till treatment due to the higher organic carbon content, however the differences were not statistically significant in the majority of cases. This is mainly due to the high scatter in the measurements using spatial replicates, which is not unusual when working under uncontrolled field conditions. Our future work should focus at the reduction of measurement uncertainty using more sophisticated and replicable measurement methods.

As main drivers of soil CO_2 emission, soil water content and soil temperature dynamics were examined. Our future aim is to test the hypothesis about the difference in NT and P CO_2 emissions using numerical simulations, but it is essential to construct accurate numerical representation of driving factors first. Our simulation results of SWC and soil temperature are encouraging, but considering the high uncertainty associated with field measurements of CO_2 as reference data, modeling errors should be minimized to obtain valuable results.

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