agrometeoros
REVISTA DA SOCIEDADE BRASILEIRA DE AGROMETEOROLOGIA
ISSN 2526-7043
www.sbagro.org.br

Evaporation of the soil water in response to the amount of straw and evaporative demand

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ARTICLE INFO

Article history:
Received 30 June 2016
Accepted 27 December 2017

Index terms:
soil management
weather variables
soil water loss
tillage system

ABSTRACT

This study aimed to evaluate the soil water evaporation in response to the amount of straw on the surface and to the atmospheric evaporative demand. Two experiments were performed in a glass greenhouse at the Federal University of Rio Grande do Sul, in Porto Alegre, Brazil, in 2003. In one experiment, the evaporation was measured with 0, 2, 4, 8 and 16 t ha^{-1} of oat straw (*Avena strigosa*) on the soil surface. In another experiment, a fixed covering of 6 t ha^{-1} of straw was used, and evaporation was measured over five soil drying cycles, displaced in time for promoting different atmospheric demands. A completely randomized design was used in both experiments. Measurements were taken by weighing PVC microlysimeters containing soil monoliths, collected in field areas previously consolidated in no-till and conventional tillage systems. The average evaporation was 24% higher in bare soil than with 16 t ha^{-1} of straw on the surface. A significant difference was observed among the evaluation cycles, but the evaporation was ever higher in conventional tillage than in no-tilled soil. The vapor pressure deficit of air and the incoming solar radiation were the most important weather variables for the evaporation, regardless of tillage system or straw presence on the soil surface.

Introduction

The evaporation of water at the soil surface is a physical process by which water changes state, from liquid to gaseous (Gupta et al., 2015; Zribi et al., 2015), without passing through the resistances and capacitances of plants, as occurs in transpiration. In vegetated areas the evaporation of soil water is higher at the beginning of the plant growth and decreases of importance with maximum leaf area (Libardi et al., 2015; Wei et al., 2015). The interactions in the soil-plant-atmosphere system that influence soil water evaporation are complex (Salado-Navaro et al., 2013; Tesfuhuney et al., 2015), which justifies being poorly studied, directly or in association with the main agricultural crops (Teng et al., 2014). Studies on the dynamics of soil water evaporation are of great importance for the management of agricultural crops, especially irrigation (Freitas et al., 2014), for modeling growth and development studies of plants (Salado-Navaro et al., 2013; Balwinder-Singh et al., 2014; Wei et al., 2015), for regional water balances (Zribi et al., 2015), among others. In addition, soil water evaporation may comprise 30% to 70% of evapotranspiration in semi-arid regions (Balwinder-Singh et al., 2011).

The response of soil water evaporation to environmental conditions is quite variable over time (Zribi et al., 2015) and from one site to another (Wei et al., 2015). It is affected by the growth and shading caused by the leaf area (Tesfuhuney et al., 2015) and by the evaporative demand of the atmosphere (Zribi et al., 2015; Tesfuhuney et al., 2015). In addition, it is influenced by factors related to the storage and movement of water into the soil profile or at the soil surface, such as porosity (Salado-Navaro et al., 2013; Gupta et al., 2015), as well as by management practices such as surface cover by straw (Tesfuhuney et al., 2015) or other materials that can interrupt or reduce the flow of water vapor from the soil to the atmosphere (Gupta et al., 2015; Zribi et al., 2015).

The evaporative demand of the atmosphere, caused by the combination of solar radiation, wind speed, air temperature and relative humidity (Teng et al., 2014; Zribi et al., 2015), and their variations over time, defines the higher or lower potential for soil water evaporation (Tran et al., 2016). However, this process only occurs if there is free water on the surface (Zribi et al., 2015) or if the physical-hydraulic properties of the soil do not limit the water demand caused by the weather conditions near the surface (Balwinder-Singh et al., 2014; Teng et al., 2014, Tran et al., 2016). In the experiment by Ward et al. (2009) the lag between evaporative demand and the ability of the soil to transfer water to the surface was considered the probable cause of the low correlation between accumulated evaporation and both the air temperature and the global solar radiation. This occurred especially when the process was in stage II of soil water evaporation, in which the importance of physical properties is greater than those of stage I (Balwinder-Singh et al., 2014).

The straw left on the soil surface in the no-tillage system changes soil-water-atmosphere relationships (Stone et al., 2006), affecting evaporation losses (Freitas et al., 2014; Tesfuhuney et al., 2015), basically in two ways. First, because it alters the action of the meteorological elements that compose the evaporative demand of the atmosphere, close to the surface (Yang & Yanful, 2002; Chen et al., 2007; Yuan et al., 2009). Secondly, it forms an insulating layer to the vapor flow, since the air that remains relatively still inside the straw (Lemon, 1956) has low vapor conduction capacity (Yuan et al., 2009). Aase & Tanaka (1987) measured the evaporation of water as a function of residues on the surface and found no significant difference between bare soil and soil submitted to different straw managements, suggesting that the straw effect was higher at the beginning of the drying process (Tesfuhuney et al., 2015). However, in a protected environment, Sauer et al. (1996) observed lower evaporation in columns of soil covered with straw, compared to those with bare soil, and that there was reduction of evaporation with increasing amount of straw on the surface, as was also verified by Ji & Unger (2001) in laboratory. Likewise, Freitas et al. (2014) found reductions in soil water evaporation, from 15% to 60% for different levels of coverage, in comparison to soil without straw, in several soil drying cycles,.

The management, quantity, quality and distribution of straw on the surface are associated to the no-tillage system (Salado-Navaro et al., 2013), which also modifies the physical and hydraulic properties of the soil and its changes with the atmosphere (Yang & Yanful, 2002; Moret & Arrúe, 2007; Freitas et al., 2014). In this sense, a large number of studies point to less evaporation in no-tilled soils (De Vita et al., 2007; Donk et al., 2010; Andrade et al., 2011), or in soil with vegetation cover (Libardi et al., 2015), in relation to the one under conventional tillage or uncovered soil. However, these findings were observed on the basis of soil moisture variations, based on one-off measures, and not by direct measurements of soil water evaporation. This is not always consistent with reality, since there are many interactions that can affect the evaporation process (Yang & Yanful, 2002), resulting in higher losses in soils under mulching than in bare soils, as a consequence of a high soil moisture, as observed by Ji & Unger (2001). Greater moisture near the soil surface in no-tillage, in comparison to conventional tillage, was also found by Dalmago et al. (2009) and Yan et al. (2009). According to Dalmago et al. (2010), the higher soil surface moisture was considered the cause of higher water evaporation in no-tilled soil than in conventional tillage. Conversely, from direct measurements of soil water evaporation, in weighing lysimeters, Freitas et al. (2014) observed greater evaporation of water in uncovered soil, compared to the soil with different percentage of coverage with straw. However, these authors did not indicate the type of soil management adopted in lysimeters, which may affect the surface evaporation process, as pointed out by Dalmago et al. (2010).

The doubts that still persist about the evaporation of groundwater require approaches allowing to understand the processes involved, which depend fundamentally on two factors: availability of water in the soil and presence of energy in the atmosphere. Other factors related to the soil-atmosphere interface, such as the presence or absence of straw, contribute to accelerate or retard the process, based on the theory presented by Lemon (1956). Thus, the presence of higher soil moisture in no-tillage than in conventional tillage, is not necessarily a condition promoted by the reduction of soil water evaporation, as has been pointed out in several studies available in the literature (Dalmago et al., 2010). On the contrary, as

Table 1. Conditions of the soil water evaporation measurement cycles in Experiment 2, by the solar radiation (SR, MJ m^{-2} day^{-1}), mean air temperature (T, °C), mean relative humidity air (RH, %) and mean air vapor saturation deficit (D, kPa) for periods of 15 days and two days. Porto Alegre, 2003.

Treatments	Total period of 15 days				Initial 2-day periods			
	SR	T	RH	D	SR	T	RH	D
Cycle I	4.5	16.5	87.7	2.8	6.5	16.5	82.8	4.4
Cycle II	4.3	16.6	88.4	2.5	4.8	17.5	87.1	3.2
Cycle III	4.2	16.8	88.7	2.5	3.7	17.9	90.9	2.4
Cycle IV	4.0	16.7	89.2	2.4	3.9	16.1	91.2	1.7
Cycle V	4.1	17.0	88.8	2.5	4.3	15.5	87.9	2.4

Total period of 15 days = measurements of evaporation in 15 consecutive days; Initial 2-day period = measurements of evaporation on two initial days, i.e. on the first two days.

pointed out by Dalmago et al. (2010), this condition may be the premise of the greater evaporative potential that no-tillage soil has, compared to conventional tillage. Also, little is known about the contribution of straw to the soil in the evaporation process. Although it plays an important role in maintaining a layer of moist soil on the surface, which can keep a higher rate of evaporation than in conventional tillage (Dalmago et al., 2010), straw also directly affects the exchange of water vapor with the atmosphere. In this way, the evaporative demand of the atmosphere is altered and, therefore, the potential of soil water evaporation is affected.

In order to elucidate some of these issues, and taking into account the doubts surrounding the evaporation of the soil water, under different systems of tillage and surface covering, this work aimed to evaluate the process of evaporation in soils subjected to no-tillage and conventional tillage, under different amounts of straw applied to the surface and variable conditions of evaporative demand of the atmosphere, in protected environment.

Material and methods

Two experiments were carried out in a greenhouse, near the experimental area of the Department of Soils, of the Federal University of Rio Grande do Sul (UFRGS), in Porto Alegre, RS (30° 05' S; 51° 39' W; 40 m), during the autumn 2003. The first study was conducted in the period from 04/03/2003 to 06/05/2003 and the second was performed from 05/29/2003 to 06/20/2003. The local climate is subtropical humid, type Cfa according to Köppen classification, with average monthly air temperature of 25 ^{0}C in January and February and 9 ^{0}C in June and July.

The greenhouse had an iron and glass structure, with a side wall of 50 cm high and a cement floor. The interior of the greenhouse was divided into two parts, and the northwestern part of it was used in the experiment. The northeast and southwest edges had windows, which were kept semi-open during the experiments, and the northwest end had a door. The glass roof had transmissivity of around 40% for global solar radiation.

The experiments were conducted in microlysimeters in a completely randomized design with three replicates, whose treatments were arranged in a two-factorial scheme. In Experiment 1, the soil preparation factor consisted of no-tillage and conventional tillage systems, while the following amounts of straw were kept on the soil surface: 0, 2, 4, 8 and 16 t ha^{-1} of straw of black oats (*Avena strigosa*), in both soil management systems. In Experiment 2, the same treatments were adopted for the soil preparation factor of Experiment 1 and, as a second factor, five cycles of soil evaporation (treatments) were evaluated for different meteorological conditions (Table 1). Each soil water evaporation measurement cycle comprised a period of 16 days, with the second cycle starting two days after the first cycle, and so on. In Experiment 2, the dose of 6 t ha^{-1} of straw was applied to the soil surface in all plots.

The soil used inside the microlysimeters was a typical Distrophic Red Argisoil. This soil had 49, 22, 29% (in no tillage) and 42, 27, 31% (in conventional tillage) of sand, silt and clay, respectively (Rojas, 1998). The field areas in which the soil was collected were submitted to no-tillage and conventional tillage systems since 1995, and it was cultivated with corn (*Zea mays*) in the warm seasons and a mixture of black oats (*Avena strigosa*) and vetch (*Vicia sativa*) in winter seasons. In the no-tillage system the winter mixture was desiccated with herbicide (glyphosate) and the straw was laid down on the soil surface. In the conventional preparation the biomass was incorporated to the soil by plow to a depth of 18 to 25 cm, followed by two passages of a disk harrow.

The microlysimeters were constructed with PVC segments, 0.15 m in diameter and 0.15 m in height, similar to those used by Boast & Robertson (1982). They were completely inserted in the soil, with a rubber mallet, and removed with the monolith formed inside. At the base of the microlysimeters a thin mesh of nylon screen was placed, to prevent soil loss and to facilitate the drainage of surplus water. The screen was attached to the outer face with plastic tape.

The microlysimeters were assembled in November

2002, during the field experiment presented by Dalmago et al. (2010), whose objective was to measure the evaporation of soil water in the field, in no-tillage and conventional tillage systems in maize crops, during the 2002/2003 cropping season. At the end of the field studies (Dalmago et al., 2010), about 120 days after being filled with soil, the microlysimeters were taken to the greenhouse, for conducting the experiments of this work. They were separated according to the soil tillage system adopted in the field and they were kept under the internal conditions of the greenhouse during all experiments. Subsequently, they remained for approximately 45 days without irrigation.

Before starting the experiments, all microlysimeters were prepared by removing the crop residues from the soil to receive the treatments with straw. The straw was collected in the experimental area in no-tillage, from where the soil monoliths were removed. It was composed basically of black oats of the winter crop of 2002. The straw was placed in a drying oven for vegetable material, with forced air flow, at a temperature of 65 ^{0}C until constant mass. After that, the treatments with straw were defined, by weighing, in precision scale. The distribution of the straw cover treatments in the microlisimeters was done by lot, considering separately the treatments of soil tillage (no-tillage and conventional tillage). After that, the straw was distributed both on the soil in no-tillage and on the soil in conventional tillage, to better study the effect of the tillage systems and the effect of the straw.

In order to standardize soil moisture, the microlysimeters were placed in plastic tanks, with constant water level to the upper edge, to saturate the soil, for 48 h. After being removed from the tanks, they were arranged in four rows, on a 80 cm high wooden bench, to drain excess water from the soil for approximately 60 h. The position of each microlysimeter on the bench was defined by lot during the installation of the experiments. However, each day, after the measurements, a rotation of the microlysimeters was performed, such that those of the central part were placed on the outside of the assembly and their position was occupied by those immediately next. The rotation was also done daily among rows, placing the outer rows in an internal position, and vice versa.

The evaporation of soil water (millimeters) was obtained by the mass difference of the microlysimeters, measured on an electronic scale with a resolution of 2 g (about 0,11 mm), with daily frequency, around 9 a.m. in the local time . The difference between days “n” and “n + 1” represented the evaporation of day “n”.

In Experiment 2, the same microlysimeters from Experiment 1 were used, as were all the procedures of that study. They were divided into five groups (Table 1), with half of each group being under no-tillage and the other half with conventional tillage. The measurement cycles of soil water evaporation were defined by a two-day lag for each group of microlysimeters. That is, the second group began to be evaluated two days after the first, the third group was evaluated two days after the second, and so on. In this way, each cycle was submitted to different meteorological conditions in the first two days of evaporation measurement. Thus, in Experiment 2 the total evaporation of soil water and evaporation of the first two days of each evaluation cycle were evaluated.

After all measurements were completed, soil density was determined by the ratio of the dry soil mass to the volume of each microlysimeter. Subsequently, the volumetric moisture was calculated for the first day of measurement, multiplying the gravimetric moisture by the density of the soil. The variation of the daily gravimetric humidity was obtained by the difference of mass of the microlysimeter between two consecutive days.

In both experiments the variables of air temperature (dry bulb), wet bulb temperature and photosynthetically active solar radiation (PAR) were measured inside the greenhouse. The air and wet bulb temperatures were measured with unventilated psychrometers and the photosynthetically active solar radiation was measured with bars containing photovoltaic cells, as described in Kunz et al. (2007), installed 1.5 m above the floor of the greenhouse. The temperature and solar radiation sensors were connected to a Campbell® datalogger, model CR10X, installed in the center of the greenhouse, taking readings every minute and storing the averages every 15 minutes, which were used to calculate the daily averages of these variables.

The daily total of photosynthetically active solar radiation (MJ m^{-2} day^{-1}) was transformed into global solar radiation (SR) by multiplying with the coefficient 1,55, considering PAR as being 45% of SR. With data of air temperature and wet bulb temperature it was possible to calculate the relative air humidity (RH, %) and the vapor saturation deficit (D, kPa) as described by Pereira et al. (1997). Also, the average daily air temperature was calculated.

The meteorological data were used to characterize the different measurement cycles of soil water evaporation from Experiment 2 (Table 1) and to correlate with soil water evaporation in each experiment. In Experiment 2, two conditions were considered: a) evaporation of the soil water in the period of 15 days (total period), considering the treatments as representative of the average condition of the 15 days; b) evaporation of soil water on the two initial days of each period (two days), considering the treatments as representative of the average condition of the two initial days. The measurement of soil water evaporation was adopted in the first two days of each

Table 2. Cumulated soil water evaporation (mm) in no-tillage system (NT) and conventional tillage (CT), measured in greenhouse with microlysimeters, during 31 days, on five different doses of straw applied on the surface [(1)]. Porto Alegre, 2003.

Accumulated evaporation of the soil water (mm)			
Doses of	Soil tillage systems		
straw (t ha^{-1})	NT	CT	Average
0	28.9	33.7	31.3 a
2	27.4	32.8	30.1 ab
4	27.6	30.6	29.1 ab
8	24.5	29.5	27.0 ab
16	24.0	26.5	25.2 b
Average	26.5 B	32.1 A	
CV (%)	11.4		

[(1)] Averages followed by equal letters, uppercase in rows and lowercase in columns, do not differ by Tukey test at 5% of error probability; CV is the coefficient of variation.

treatment of Experiment 2 because the evaporation in these two days can be considered independent, among the evaluation cycles.

The average soil water evaporation, measured in both experiments, was submitted to analysis of variance and the means were compared by the Tukey test at 5% error probability, and also by regression analysis and Pearson correlation. In Experiment 1, the total evaporation of the measurement period and the daily evaporation were evaluated. In Experiment 2 the evaporation of the entire period and that of the first two days after the beginning of measurements were evaluated.

Results and discussion

The accumulated evaporation of soil water measured in the period of Experiment 1 did not show interaction between treatments (Table 2). This indicates that the influence of straw on the dynamics of soil water evaporation was the same in both soil tillage systems. In general, straw cover reduces evaporation of soil water by reducing the transport of vapor from the soil surface to the atmosphere, forming an insulating layer (Lemon, 1956; Yuan et al., 2009) and reducing the availability of energy and the gas exchange in the air layer near the straw (Yang & Yanful, 2002).

Among the soil management systems, evaporation was significantly higher in the conventional tilled soil, about 20%, compared to under no-tillage, due to the higher soil moisture at the beginning of the evaluations, as observed on the first day of (Table 3), when it was higher in 8.8% in conventional tillage than in no-tillage. On the last day of measurements, there was no significant difference in soil moisture between no-tillage and conventional tillage (Table 3), probably due to the high evaporation rates of the soil in conventional tillage at the beginning of the evaluations. Therefore, the higher amount of water in the soil under conventional tillage was the main cause of the significant difference in evaporation observed between soil management systems.

The results of both moisture retention and soil water evaporation tended to be contrary to those reported by Dalmago et al. (2009) and Dalmago et al. (2010), respectively, for the same soil. In the experiments of this work, the capillary saturation method may have contributed to increase soil water retention in conventional tillage due to differences in the porosity distribution, between the two management systems (Kay & Vandenbygaart, 2002; Hubert et al., 2007; Dalmago et al., 2009). According to Kay & Vandenbygaart (2002) and Hubert et al. (2007), the soil porosity in no-tillage shows greater tortuosity, because a large part of the pores is caused by the activity of microorganisms and by the action of roots. Meanwhile, in conventional tillage the porosity of the soil is more linear than in no-tillage, mainly due to the arrangement of the mineral particles and soil aggregates. The tortuosity of

Table 3. Soil moisture (cm^{3} cm^{-3}) in no-tillage system (NT) and conventional tillage (CT), with different doses of straw applied to the surface, on the first and last day of evaporation measurements, in the first experiment[(1)]. Porto Alegre, 2003.

Doses of	First day of measurements			Last day of measurements		
straw (t ha^{-1})	NT	CT	Average	NT	CT	Average
0	0.297	0.302	0.299 b	0.084	0.079	0.081 c
2	0.294	0.334	0.314 ab	0.094	0.098	0.096 bc
4	0.291	0.324	0.308 ab	0.093	0.118	0.106 ab
8	0.317	0.360	0.339 a	0.140	0.119	0.130 ab
16	0.332	0.345	0.338 a	0.154	0.151	0.153 a
Average	0.306 B	0.333 A		0.113 A	0.113 A	
CV (%)			6.62			24.40

Means followed by equal letters, uppercase in lines (at each moment of measurement of soil moisture - first or last day) and lowercase in columns, do not differ by Tukey test at 5% probability of error; CV is the coefficient of variation.

Table 4. Evaporation of soil water (mm) in no-tillage system (NT) and conventional tillage (CT), measured during 15 days (total evaporation) and evaporation measured in the first two days in five evaluation cycles in 2 days) (1). Porto Alegre, 2003.

Evaluation cycles	Condition for evaporation measurements			
	Total evaporation - 15 days (mm)		Evaporation in 2 days (mm)	
	NT	CT	NT	CT
I	8.7 a B	16.8 a A	1.0 ab B	1.8 a A
II	6.0 ab B	12.5 b A	0.6 b B	1.2 bc A
III	4.9 b B	12.4 b A	0.6 b B	1.7 ab A
IV	5.4 b B	09.5 c A	1.1 ab A	0.7 c A
V	4.6 b B	09.6 c A	1.2 a B	2.0 a A
CV (%)	11.6		15.7	

Means followed by equal letters, lowercase in the columns and uppercase in the rows, within each soil water evaporation measurement condition, do not differ by Tukey test at 5% probability of error; CV is the coefficient of variation.

the pores makes it difficult to expel air during saturation, whereas more linear pores favor this process and so the soil saturation. This hypothesis is reinforced by the lower soil density in no-tillage (1.42 Mg m^{-3}), when compared to conventional tillage (1.53 Mg m^{-3}).

Considering the treatments of straw doses, the highest and lowest values of evaporation of water were observed with 0 t ha^{-1} and 16 t ha^{-1} of straw, respectively (Table 2). These values indicate a significant reduction of soil water evaporation by about 19.5%, although these extremes did not differ from the intermediate treatments. Similar results, showing reduction of soil water evaporation by surface straw in the field, were presented by Chen et al. (2007) and Balwinder-Singh et al. (2011), from measurements in microlysimeters, and by Gava et al. (2013) and Freitas et al. (2014) in weighing lysimeters, using quantities of straw of less than 16 t ha^{-1} from different agricultural crops.

The evaporation of water in the bare soil was greater than that of the 16 t ha^{-1} treatment of straw on the surface, even though it presented lower moisture on the first day of measurements, compared to treatments of 8 and 16 t ha^{-1} of straw on the surface (Table 3). Based on these results, and considering that the soil moisture on the last day of measurements was significantly lower in the treatment of 0 t ha^{-1} than in treatments of straw dose higher than 2 t ha^{-1}, it can be stated that straw in the soil surface decreased the loss of water by evaporation, with significant effect for quantities close to 16 t ha^{-1}. However, if the soil moisture is considered as an indicator of evaporation, the dose of 8 t ha^{-1} of straw has already shown a significant effect on the reduction of soil moisture loss. Both amounts of straw are above the values added annually on the soil, which are around 5 t ha^{-1} (Freitas et al., 2014). This result is in agreement with both results obtained by Balwinder-Singh et al. (2011) in microlysimeters, from 8 to 9 t ha^{-1} of rice straw, as well as results from Freitas et al. (2014), with a maximum of 10 t ha^{-1} of wheat straw. However, it differs from those of Andrade et al. (2011), who found a reduction of 40% in water losses with 6 and 10 t ha^{-1} of oat straw, at the initial stage of corn development, based on soil moisture measurements. Thus, interpretations on soil water evaporation may be different if they are taken from point measurements of soil moisture or from direct measurements of evaporation at the soil surface (Dalmago et al., 2010).

The relative reduction of soil water evaporation as a function of the amount of straw applied to the surface was adjusted to a second degree polynomial function (Figure 1). By solving the equation, the maximum evaporation reduction was 19.66% with an approximate amount of 18 t ha^{-1} of straw on the soil surface. Considering the limit of 10 t ha^{-1} to 12 t ha^{-1} of straw left on the soil surface, for a year, the reduction of soil water evaporation varies between 15.46% and 17.21%. This means 4.2 to 2.5 percentage points less than the reduction of evaporation with 18 t ha^{-1} of straw on the surface, pointed as the limit in this work. According to data from Balwinder-Singh et al. (2011) and Freitas et al. (2014), obtained in microlysimeters / lysimeters, 10 t ha^{-1} of straw on the soil surface is the limit for the maximum reduction of water evaporation, in relation to the soil without straw.

In Experiment 2, evaporation showed interaction between soil management systems and evaluation cycles, both for the total evaporation measured in the period of 15 days, and for the evaporation measured in the first two days of each cycle. In the two conditions (total of 15 days and two initial days), the evaporation was 30% to 60% higher in conventional tillage than in no-tillage in all evaluation cycles, except in cycle IV of the condition of two initial days, in which it was higher in no-tillage than in conventional tillage (Table 4). The higher evaporation in the soil in conventional tillage can be attributed to the more linear form of the pores, which facilitates the diffusion of water vapor from the interior of the soil to the surface, in comparison to that in no-tillage, whose pore geometry tends to be more chaotic, obstructing or hindering the flow of vapor to the surface, due in large part to being of biological origin (Kay & Vandenbygaart,

Figure 1. Average percentage of reduction in water evaporation from soils subjected to no-tillage (NT) and conventional tillage (CT) systems, as a function of different amounts of straw on the surface. Porto Alegre, 2003.

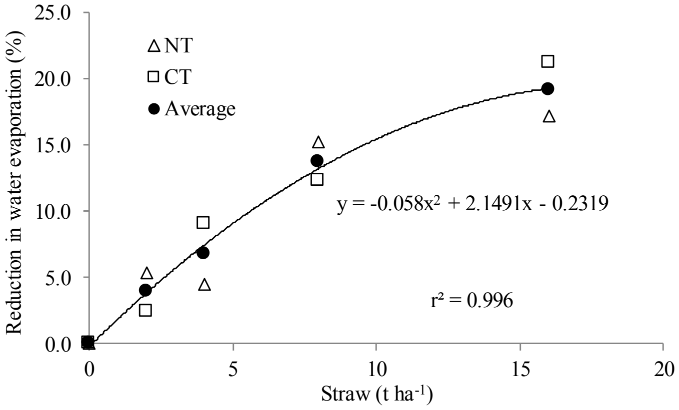

Table 5. Soil moisture (cm^3 cm^{-3}) within the microlysimeters of the no-tillage (NT) and conventional tillage (CT) treatments, in the first day of measurements and in the average of the first two days, in five evaluation cycles$^{(1)}$. Porto Alegre, 2003.

Evaluation cycles	Soil moisture (cm³ cm⁻³)			
	First day of measurements		Average of the initial 2 days	
	PD	PC	PD	PC
I	0.291 a B	0.359 a A	0.287 a B	0.350 a A
II	0.304 a A	0.334 ab A	0.297 a A	0.327 ab A
III	0.301 a A	0.324 ab A	0.297 a A	0.318 ab A
IV	0.309 a A	0.285 b A	0.302 a A	0.279 b A
V	0.283 a A	0.322 ab A	0.282 a A	0.311 ab A
CV (%)	6.1		6.1	

Means followed by equal letters, lowercase in the columns and upper case in the rows, within each soil water evaporation measurement condition, do not differ by Tukey test at 5% probability of error; CV is the coefficient of variation.

2002). This hypothesis is reinforced by the fact that soil moisture inside the microlysimeters did not present a significant difference (Table 5), except in cycle I, because this treatment was the first, when the environment had a high evaporative demand (Table 1).

The water evaporation was higher in the evaluation cycles I and II, in no-tilled soil, and in the cycle I, in conventional tillage, in comparison to the other cycles. However, in the two-day measurement conditions, the process did not present significant difference among cycles I, IV and V, in no-tilled soil, and in cycles I, III, V, in conventional tillage, in relation to the other treatments (Table 4). These differences clearly demonstrate the effect of evaporative atmospheric demand on the soil water evaporation (Song et al., 2014; Aydin et al., 2015), since there was no significant difference in soil moisture in no-tillage among the evaluation cycles, except in cycle IV for the soil under conventional tillage (Table 5). Thus, if water is available on the soil surface (Zribi et al., 2015), the meteorological conditions define the potential for evaporation (Balwinder-Singh et al., 2014; Song et al., 2014; Teng et al., 2014; Tran et al., 2016), especially in stage I (Tesfuhuney et al., 2015) as described by Lemon (1956).

For both experiments, the two main meteorological variables that governed soil water evaporation were the vapor saturation deficit and the incident solar radiation (Table 6). These variables had the highest and positive correlation coefficients for all cases, indicating that their increases promote increases in evaporation of the soil water, since there is moisture available on the surface. It was also evident that, except in some cases, the correlation coefficients were similar in the conditions under which the soil was submitted, in no-tillage and conventional tillage. This confirms that, in both soil preparation systems, evaporation was strongly dependent on the availability of energy (solar radiation) (Banimahd & Parsa, 2013) and on the evaporating power of air (water vapor saturation deficit), considering that the wind was reduced in the protected environment, which would not occur in the field, where it should be the second forcing variable for the transport and removal of water vapor, close to the surfaces.

Considering the soil preparation systems, the correlation coefficients between evaporation and the two main meteorological variables that controlled soil water loss (in the protected environment) was higher in the treatments with addition of straw to the surface, compared to bare soil. This difference between straw and non-straw

Table 6. Coefficients of Pearson correlation between soil water evaporation and the mean values of air temperature (Tm), minimum temperature (Tn), maximum temperature (Tx), relative humidity (RH), vapor saturation deficit (D) and global solar radiation (SR), for the experiments of straw dose (0, 2, 4, 8, 16 t ha^{-1}) and evaluation cycles (I, II, III, IV and V). Porto Alegre, 2003.

Treatments	Coefficients of Pearson correlation											
	No-tillage						Conventional tillage					
	T	Tn	Tx	RH	D	SR	T	Tn	Tx	RH	D	SR
	Experiment 1 – Doses of straw on the soil surface (t ha^{-1})											
0	-	0.39	-0.35*	-0.48	0.49	0.75	-	0.35*	-	-0.41	0.43	0.65
2	-	0.44	-0.42	-0.65	0.63	0.83	-	0.37	-0.44	-0.66	0.60	0.81
4	-	0.39	-0.45	-0.69	0.63	0.82	-	0.40	-0.45	-0.68	0.63	0.82
8	-	0.56	-0.50	-0.73	0.75	0.88	-	0.51	-0.48	-0.74	0.73	0.86
16	-	0.47	-0.44	-0.67	0.67	0.81	-	0.51	0.47	0.70	0.69	0.85
	Experiment 2 – Evaluation cycles of evaporation											
I	-	0.72	-	-0.83	0.89	0.82	-	0.66	-	-0.89	0.89	0.84
II	-	-	-	-0.68	0.68	0.66	-	0.65	-	-0.81	0.91	0.77
III	0.50*	0.64	-	-	0.58	0.60	-	0.60	-	-0.55	0.72	0.60
IV	-	-	-	-	-	0.46*	-	-	-0.45*	-0.62	0.59	0.79
V	-	-	-	-	-	0.49*	-	-	-	-0.58	0.55	0.59

Note: Only the coefficients of Pearson correlation significant at 5% and 10% (*) of error probability are presented.

treatments, in terms of soil water evaporation, can be attributed to the presence of a drier layer on the surface of the bare soil, which interrupts the water flow from the interior of the soil profile (Lascano & Van Bavel, 1986). In this condition, in soil without protection by straw or other material, the evaporation of the water occurs inside the profile and the water vapor is transferred to the atmosphere by diffusion, in a slower process than the transport by mass flow, and even more slower than evaporation at the soil-atmosphere interface, where convection favors the transfer of vapor into the atmosphere. With the presence of straw on the soil, as occurs in a well-managed no-tillage system, the water flow from the soil interior is maintained to the surface and evaporation tends to predominate at the soil-straw-atmosphere interface. As in the surface there is a greater amount of energy available for evaporation of the water than in the soil profile, and the air presents a higher water demand, since the convective processes are more active, the rate of soil water loss under no-tillage can be more higher than in conventional tillage, assuming field conditions and a long period of soil drying (Dalmago et al., 2010). Therefore, a better correlation (Table 6) is expected between evaporation in soil with surface residues and meteorological variables, than in bare soil, even in controlled environment conditions.

In Experiment 2, with variation in atmospheric evaporative demand, the correlation coefficients did not present the same trend, since all the evaluation cycles were established with the same amount of straw on the soil surface. Thus, the correlation coefficients reflect the relationship between the evaporation occurred in each treatment and the respective meteorological conditions of each evaluation cycle, mainly the air vapor saturation deficit and the incident solar radiation, evaluated in this case (Table 1), and, probably, the wind in field conditions.

The results of soil water evaporation obtained in this work, in a controlled environment, are in opposition to those found by Dalmago et al. (2010) in the field. Meanwhile, the evaporation of soil water in the field was higher in no-tillage system, compared to the conventional tillage system (Dalmago et al., 2010), and in this work it was the opposite (Table 2). This can be attributed to the evaporative demand conditions of the atmosphere, which were less intense inside the greenhouse than in the field. With lower evaporative demand, soil drying is less intense and the hydraulic conductivity of the soil is able to supply water to the surface, hindering the formation of a dry soil layer, which would make it difficult to lose water vapor, reducing evaporation of uncovered soil water. In addition, in the field, the soil water supply was made via irrigation and / or through rainfall (Dalmago et al., 2010), while in the controlled environment, soil saturation was promoted by flooding. This may have also been a factor responsible for the differences in total soil water evaporation between the environments, since flooding is more efficient in soil pore saturation than irrigation and / or rainfall. However, considering the process over time, when there is water and energy available on the surface, as occurs shortly after an irrigation or rainfall (Dalmago et al., 2010) or in conditions of low evaporative demand of the atmosphere, the evaporation of water from the soil tends to be higher in conventional tillage than in no-tillage.

Conclusions

1. Evaporation of water at the soil surface is higher in soils subjected to the conventional tillage than in no-tillage system.

2. Significant reductions in losses by water evaporation may occur in no-tilled soils with more than 8 t ha^{-1} of straw covering the surface.

3. Conditions of atmospheric evaporative demand determine the magnitude of the evaporation of soil water, regardless of the surface coverage.

4. In a protected environment, the air vapor saturation deficit and incident solar radiation are the most influencing meteorological variables on the evaporation of water on the soil surface, in both no-tillage and conventional tillage systems.

Acknowledgments

To the National Council for Scientific and Technological Development of Brazil (CNPq) for the financial support in the execution of the field works, and for the doctoral and research productivity scholarships for the authors.

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CITATION

DALMAGO, G. A.; BERGAMASCHI, H. Evaporation of the soil water in response to the amount of straw and evaporative demand. **Agrometeoros**, Passo Fundo, v.25, n.2, p.361-371, 2017.

Evaporação da água do solo em resposta à quantidade de palha e à demanda evaporativa

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INFORMAÇÕES

História do artigo:
Recebido em 30 de Junho de 2016
Aceito em 27 de Dezembro de 2017

Termos para indexação:
manejo do solo
variáveis meteorológicas
perda de água do solo
sistemas de preparo

RESUMO

Este estudo teve por objetivo avaliar a evaporação da água do solo em resposta à quantidade de palha na superfície e à demanda evaporativa da atmosfera. Dois experimentos foram conduzidos em estufa de vidro na Universidade Federal do Rio Grande do Sul, em Porto Alegre, Brasil, em 2003. Num experimento a evaporação foi medida com 0, 2, 4, 8 e 16 t ha^{-1} de palha de aveia (*Avena strigosa*) sobre o solo. No outro, usou-se uma cobertura fixa de 6 t ha^{-1} de palha, e a evaporação foi medida em cinco ciclos de secagem do solo, defasados no tempo para promover diferentes demandas atmosféricas. Um delineamento inteiramente casualizado foi usado nesses experimentos. As medidas constaram da pesagem de microlisímetros PVC contendo monólitos de solo, coletados no campo em áreas consolidadas em sistemas de plantio direto e preparo convencional. A evaporação média foi 24% maior em solo desnudo que com 16 t ha^{-1} de palha sobre a superfície. Houve diferença significativa entre ciclos, mas a evaporação foi sempre maior no preparo convencional que em plantio direto. O déficit de pressão de vapor do ar e a radiação solar incidente foram as principais variáveis meteorológicas para a evaporação, independentemente de sistemas de preparo ou presença de palha na superfície.

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