Evapotranspiration changes in the forest-steppe and steppe zones under soil mulching

Nadezhda Shumova

Water Problems Institute, Russian Academy of Sciences, Gubkin St. 3, 119333 Moscow, Russia; E-mail: shumova@aqua.laser.ru

Abstract: This paper contains the method and results of calculation evapotranspiration and its structure – transpiration and evaporation from traditionally tilled and mulched soil. The data considered indicate that in the arid regions of territory under study the evapotranspiration when soil is mulched does not change significantly and only the relation between the transpiration and soil evaporation changes. In the wet regions, evapotranspiration decreases when the soil is mulched which can result in a certain disturbance of the natural structure of the hydrological cycle and possible overmoistening soils.

Keywords: Evapotranspiration; Evapotranspiration structure; Traditional agricultural practice; Soil mulching.

INTRODUCTION

The abundance of light and heat together with high soil productivity promoted the transformation of the southern Russian regions into an agricultural landscape. But these regions are characterized by insufficient precipitations (Shumova, 2001), which led to a wide-spread irrigation. The economic activities resulted in the local land overmoistening and salinization leading to the degradation of high-productive chernozem soils and removal of land from the agricultural use. Recently, in the agricultural production, the interest is paid to the nature friendly agricultural practice associated with the minimum man impact on the environment (Agricultural ecosystems, 1987). Natural ecosystems have on the soil surface a layer of felt and a litter of died-of plant mass, which allows them to optimally use the biosphere resources. Using the technology of a direct seeding and minimal soil treatment (Allen, 1985) with soil mulching as one of its links, the agroecosystem can be brought to a more natural form.

The soil mulching promotes a substantial decrease in soil evaporation and an increase in transpiration, which results in the enhanced water supply of agricultural crops (Shumova, 1997). If under conditions of traditional agricultural practice in the forest-steppe and steppe zones part of transpiration to evapotranspiration in the spring wheat field amounts to 30–40% (Shumova, 2000) then in case of soil mulching with the straw it can amount to more than 60% (Shumova, 1997). However, a question is whether the magnitude of the evapotranspiration under soil mulching is changing or the structure of evapotranspiration changes. Presently, the problem is vital, as the reduced evapotranspiration in case of the soil mulching can result in the changed structure of a hydrological cycle: in the water accumulation in the soil, which is undesirable under conditions of the modern hydromorphism (Novikova and Nazarenko, 2007). Theoretical basis of the calculation method used in this paper is presented in papers of Budagovskiy and Novak (2011a,b). The objective of this work is to estimate the influence of soil mulching on the spring wheat field evapotranspiration in the forest-steppe and steppe zones. The problem is based on the numerical experiment, which to the evapotranspiration calculation under conditions of a traditional agricultural practice and soil mulching. The approach used in this work allows accounting for quantitative demands to the evapotranspiration of agricultural crops during their development.

METHOD

The evapotranspiration E in a general case includes the soil evaporation E_s and the transpiration E_t (Budagovskiy, 1964; Shumova, 2003)

$$E = E_s + E_t. \quad (1)$$

The empirical formulas (Budagovskiy, Shumova, 1976) are used for calculating soil evaporation

$$E_s = E_{s0} \left(\gamma V e^{-P/E_{s0}} + 1 - e^{-P/E_{s0}} \right), \quad (2)$$

$$E_{s0} = b_1 \Phi_s D_s d + b_2 (R e^{-s\omega} - B), \quad (3)$$

$$\Phi_s = e^{-1.1\omega}, \quad (4)$$

$$D_s = \frac{0.8u}{u^{1/2} + 0.7}, \quad (5)$$

$$b_1 = \frac{0.7}{1 + 1.56\phi}, \quad b_2 = \frac{0.026\phi}{1 + 1.56\phi}, \quad (6)$$

$$\phi = \frac{24513}{(235 + T)^2} e^{\frac{17.1T}{235+T}}, \quad (7)$$

where E_{s0} is potential soil evaporation (mm day⁻¹), γ is empirical parameter dependent on hydrophysical soil properties (mm⁻¹), V is available soil water storage of soil root layer (mm), P is precipitation (mm day⁻¹), b_1 and b_2 are function of air temperature, Φ_s is function of the leaf area index, D_s is function of wind speed, d is air humidity deficit at 2 m (mb), R is net radiation (cal cm⁻² day⁻¹), S is coefficient dependent on the geographical latitude and season of year (Budagovskiy, 1964), ω is leaf area index (cm² cm⁻²), B is heat flux in the

soil ($\text{cal cm}^{-2} \text{ day}^{-1}$), u is wind speed at 2 m (m s^{-1}), ϕ is the slope of the saturated water vapor pressure as a function of air temperature ($\text{mb } ^\circ\text{C}^{-1}$), T is air temperature at 2 m ($^\circ\text{C}$).

Transpiration is calculated as follows

$$E_t = \begin{cases} E_{t0} & \text{at } V \geq V_{cr} \\ E_{t0} \frac{V}{V_{cr}} & \text{at } V < V_{cr} \end{cases}, \quad (8)$$

$$E_{t0} = b_1 D_\omega \Phi_1 d + b_2 \left[R(1 - \Phi_2 e^{-s\omega}) - (1 - \Phi_2) B \right] - (1 - \Phi_2) E_s, \quad (9)$$

$$D_\omega = \frac{c_1 \tilde{u}}{c_2 \tilde{u}^{1/2} + 1}, \quad \tilde{u} = u + 0.4, \quad (10)$$

$$\Phi_1 = (1 - e^{-\omega}), \quad \Phi_2 = e^{-0.25\omega}, \quad (11)$$

where E_{t0} is potential transpiration (mm day^{-1}), V_{cr} is critical available soil water storage (mm), D_ω and $\tilde{u}$ are function of wind speed, Φ_1 and Φ_2 are functions of the leaf area index, $c_1 = 2.4$, $c_2 = 4 \text{ m}^{1/2} \text{ s}^{-1/2}$ are coefficients determined from the field experiments.

Critical available soil water storage in a one meter soil layer are described with the relation

$$V_{cr} = 60 + 4.2 E_0, \quad (12)$$

$$E_0 = b_1 D_\omega \Phi_1 d + b_2 (R - B), \quad (13)$$

where E_0 is potential evapotranspiration (mm day^{-1}).

Available soil water storage is determined according to the formula (Budagovskiy and Shumova, 1976)

$$V_e = (V_b + k/m) e^{-m\tau} - k/m, \quad (14)$$

where V_e and V_b are available soil water storage (mm), at the beginning and at the end of the calculation time interval, respectively, τ is time interval (day).

If the available soil water storage is above or equal to its critical values $V \geq V_{cr}$, calculated in accordance with (12) and (13), k and m are calculated with the relations

$$k = b_1 D_\omega \Phi_1 d + b_2 \left[R(1 - \Phi_2 e^{-s\omega}) - (1 - \Phi_2) B \right] + \Phi_2 (1 - e^{-P/E_{s0}}) E_{s0} - P, \quad (15)$$

$$m = \Phi_2 \gamma E_{s0} e^{-P/E_{s0}}. \quad (16)$$

In the case of the available soil water storage is below its critical value $V < V_{cr}$, k and m are calculated with the formulas

$$k = (1 - e^{-P/E_{s0}}) E_{s0} - P, \quad (17)$$

$$m = \frac{1}{V_{cr}} \left\{ b_1 D_\omega \Phi_1 d + b_2 R(1 - \Phi_2 e^{-s\omega}) - (1 - \Phi_2) \left[(1 - e^{-P/E_{s0}}) E_{s0} + b_2 B \right] \right\} + \gamma E_{s0} e^{-P/E_{s0}}. \quad (18)$$

The calculation is performed with a ten day time step and covers a frost-free period (a period between a complete snow melting in spring and appearance of air temperature below zero in autumn). First, soil water storage then, soil evaporation and transpiration are calculated. A detailed assessment of the accuracy of the calculation scheme described is given in Shumova (2003).

In case of the soil mulching, the scheme of the evapotranspiration calculation given above is used too. The differences are only in the use of other relations describing the soil evaporation. The estimation of the soil evaporation in case of mulching is based on the formula describing evaporation through a dried-up soil layer (Budagovskiy, 1964), which for the mulching conditions is written (Budagovskiy and Grigorieva, 1991):

$$E_{s(m)} = \frac{E_{s0}}{1 + \beta z_m}, \quad (19)$$

where $E_{s(m)}$ is soil evaporation under soil mulching, β is parameter depending on diffusivity of water vapour in the mulch layer and on its heat conductivity, z_m is thickness of the mulch layer.

It should be taken into account that after each rainfall the mulch itself also retains some precipitation amount. On that basis two stages of the soil evaporation are considered in the presence of the mulch. The first stage is evaporation resulted

Fig. 1. Location of agrometeorological stations (AS). Dotted lines denote the boundaries of the forest-steppe and steppe zones (Berg, 1947; Berg, 1952). Circles denote agrometeorological stations with average annual data used for calculations; Full circles denote the AS annual data; 1 – Kazan, 2 – Mikhailov, 3 – Samara, 4 – Bezenchuk, 5 – Orenburg, 6 – Glukhov, 7 – Saratov, 8 – Nizhnedevitsk, 9 – Ershov, 10 – Uralsk, 11 – Kamennaya Step, 12 – Vladimir-Volynskiy, 13 – Mironovka, 14 – Poltava, 15 – Dzhanibek, 16 – Belovodsk, 17 – Novaya Ushitsa, 18 – Kirovograd, 19 – Konstantinovskiy, 20 – Kharabali, 21 – Mariupol, 22 – Kishinev, 23 – Kherson, 24 – Gigant, 25 – Odessa, 26 – Sarata, 27 – Krasnodar, 28 – Zolotushka.

Fig. 2. Average annual values (a) and annual values (b) of the spring wheat field evapotranspiration in the case of the traditional agricultural practice E and from mulched soil E_m .

from the mulch drying, and the second stage is soil evaporation through the mulch layer. The first stage, the evaporation of the precipitation retained by the mulch is described with the formula (Budagovskiy and Grigorieva, 1991)

$$\int_0^t E_{s(m)} dt = \frac{1}{\gamma_m} \left(\sqrt{1 + 2\gamma_m \int_0^t E_{s0} dt} - 1 \right), \quad (20)$$

where γ_m is parameter that depends on the mulch ability to retain water; its value is $2.8 - 4.0 \text{ cm}^{-1}$. After the mulch layer is completely dried, the soil, according to (19), is evaporated through it. The total soil evaporation consists of the evaporation of precipitation retained by the mulch layer and water evaporated by the soil through this layer.

The reference time starts at the moment the rain ceases, and the time interval, for which the calculation is performed, estimated by the division of the total duration of the calculation time by the number of rains within it. Practically, when calculating soil evaporation in the presence of mulch, it is convenient to use the monthly precipitation totals and the data on the number of rains with $P > 0.1, 0.5, 1.0, 5.0, 10.0, 20.0$, and 30.0 mm. In this case, the result of calculations are monthly values of the soil evaporation; the ten day values are determined from the monthly values proportionally to the ten day values E_{s0} .

When using the straw mulch (as the most attractive from the ecological viewpoint), according to the numerical experiments (Dzhogan nad Gusev, 2003; Gusev and Dzhogan, 2000), the thickness of its layer noticeably influences the soil evaporation only up to the thickness 4–5 cm. Thus, a 4–5 cm straw mulch layer (which corresponds to a mass of 10 t ha^{-1}) is optimal that practically results in the maximally possible reduction in the soil evaporation.

The technique of calculations of the evapotranspiration and soil water storage in the presence of the mulch is the following. The soil evaporation $E_{s(m)}$, as was shown above, is determined independently from the precipitation and potential soil evaporation E_{s0} , which is determined using Eq. (3). The transpiration $E_{t(m)}$ is determined from the relation similar to (8), which in case of mulching becomes as follows

$$E_{t(m)} = \begin{cases} E_{t0(m)} & \text{at } V \geq V_{cr} \\ \frac{V}{V_{cr}} E_{t0(m)} & \text{at } V < V_{cr} \end{cases}, \quad (21)$$

where $E_{t0(m)}$ is potential transpiration with the soil mulching. Similarly to Eq. (9), it should be written for the mulching

$$E_{t0(m)} = b_1 D_{\omega} \Phi_1 d + b_2 \left[R(1 - \Phi_2 e^{-s\omega}) - (1 - \Phi_2) B \right] - (1 - \Phi_2) E_{s(m)}. \quad (22)$$

The available soil water storage under conditions of the sufficient water content $V \geq V_{cr}$ can be determined from the water balance relation

$$V_e = V_b + (P - E_{s(m)} - E_{t0(m)})\tau. \quad (23)$$

Fig. 3. Average annual values E_m / E . Full circles denote the cases when $E_m = E$.

When available soil water storage is below critical values $V < V_{cr}$, available soil water storage is determined by formula (14) at

Fig. 4. Spring wheat field annual evapotranspiration for a frost-free period in the case of the traditional agricultural practice E (circles) and soil mulching E_m (full circles).

Table 1. Interannual variability of the spring wheat field evapotranspiration under a traditional agricultural practice and soil mulching.

Station number	Station	Traditional agricultural practice			Soil mulching		
		$\bar{E}$ (mm)	σ_E (mm)	$C_{V(E)}$	$\bar{E}_m$ (mm)	σ_{E_m} (mm)	$C_{V(E_m)}$
4	Bezenchuk	340	56	0.16	334	37	0.11
9	Ershov	305	78	0.26	308	51	0.17
11	Kamennaya Step	388	58	0.15	363	39	0.11
13	Mironovka	456	58	0.13	374	14	0.04
24	Gigant	404	62	0.15	396	26	0.07
25	Odessa	387	58	0.15	376	29	0.08

Note: $\bar{E}$ and $\bar{E}_m$ are average values, σ_E and σ_{E_m} are standard deviations, $C_{V(E)}$ and $C_{V(E_m)}$ are variation coefficients.

$$k = E_{s(m)} - P, \quad (24)$$

$$m = E_{t0(m)} / V_{cr}. \quad (25)$$

Evapotranspiration, as in case of the traditional agricultural practice, is calculated with a ten day time step and covers a frost-free period.

The evapotranspiration calculations are based on standard observations of agrometeorological and actinometrical stations.

The leaf area index is determined according to Shumova, (2003). Under conditions of the traditional agricultural practice (in the absence of mulching layer), the soil water storage values measured at the agrometeorological stations are taken in all cases as initial conditions. In the presence of the mulch the selection of the initial soil water storage that start the calculation has the following characteristic features.

Selection of the initial soil water storage V_b , in the first ten day after complete melting of the snow cover in spring, should correspond to the same value as under conditions of the tradi-

tional agricultural practice. When performing the calculations for several years, in the first year, the first measured soil water storage is taken as the initial water storage V_b . To determine the initial soil water storage in the next year, the spring soil water content, observed under traditional agricultural practice, is added to the final soil water storage V_e , which are observed in the last ten days with air temperature above zero in the previous autumn

$$V_{b(i)} = V_{e(i-1)} + \Delta V_w, \quad (26)$$

where $V_{b(i)}$ is initial (spring) soil water storage of the current year, $V_{e(i-1)}$ is final (autumn) soil water storage of the previous year, ΔV_w is spring soil water change in the case of traditional agricultural practice. To determine the initial soil water storage, which start the calculations, the condition $V_b \leq V_{fc}$ should be valid, where V_{fc} is the field capacity.

The basic parameters of the evapotranspiration estimation are universal, i.e., they can be used for calculations in different physic-geographical zones. With this scheme one can estimate the total soil water storage that include both the productive component of soil water storage (available water for plants) and unavailable water for plants (immobile water). The modifica-

tion of the above scheme can be used for detail study of the water balance formation in the root layer in case of mulching (Gusev and Dzhogan, 2000); the scheme provides a detail description of physical processes in mulch layer and in the soil under the mulch in the frost-free period and for estimating the influence of a straw mulch on the soil water replenishment in spring to use a complex of models of the soil water formation in the winter-springtime as suggested in Gusev (1993).

RESULTS AND DISCUSSION

The average annual values of the spring wheat field evapotranspiration were calculated by the above relations, using the data from 28 agrometeorological stations (Fig. 1); for six of these stations (Bezenchuk, Ershov, Kamennaya Step, Mironovka, Gigant, and Odessa) the evapotranspiration was calculated for individual years. The calculations are performed in two variants: in the absence of the mulching cover and in the presence of a 5-cm layer of the straw mulch.

Fig. 2a) shows relations between average annual values of the spring wheat field evapotranspiration for a frost-free period under conditions of the traditional agricultural practice E and the soil mulching E_m . The points in the graph lie on the line starting from the axis cross-section at an angle of 45° and below this line. It indicates the fact, that evapotranspiration for a frost-free period in case of the soil mulching either retains its initial value or decreases compared to evapotranspiration under conditions of a traditional agricultural practice. Mulch water

Fig. 5. Spring wheat field annual evapotranspiration probability curves of a frost-free period in the case of the traditional agricultural practice E (circles) and soil mulching E_m (full circles).

evaporation calculated from the actual rain event does not reach 4 mm. An exception are eight months out of 197 considered (in 4% of cases), when evaporation exceeds 4 mm for each rain. This implies that in the average annual conditions, only the precipitation retained in the mulch is evaporated, i.e., the first stage of evaporation (described by (20)) takes place.

Fig. 3 shows a spatial distribution of average annual values of the relations E_m / E . The equality $E_m / E = 1$ is characteristic of the arid part of the area under study, while the wet regions are characterized by $E_m / E < 1$. On average, in case of the soil mulching this ratio in the forest-steppe and steppe zones can be 0.94, i.e., the evapotranspiration in a case of the soil mulching can decrease by 6%. In the average, the evapotranspiration at certain stations can decrease for a frost-free period to 23–25% (Vladimir-Volynskiy and Krasnodar stations), which in absolute values amounts to 105 and 135 mm, respectively.

Fig. 4 can give an idea for individual years between the evapotranspiration with the traditional agricultural practice and in case of the soil mulching. In individual years the mulching leads to the decreased evapotranspiration and then the water accumulated in the soil can lead to its increase (as a result of the transpiration increase). It is mainly characteristic of the Bezenchuk and Ershov stations in the arid zone. At the Kamennaya Step and Mironovka stations, in most cases, the evapotranspiration noticeably decreases in the presence of the mulch. It is illustrated by the graph in Fig. 2b). The maximum decrease of the evapotranspiration over a number of the years studied ranged in case of mulching from 53 mm (Bezenchuk station) to 124 mm (Mironovka station).

The probability curves shown in Fig. 5 also give an idea of inter-annual variability of the evapotranspiration when traditional agricultural practice and soil mulching is used. The analysis of results demonstrated (Fig. 5 and Table 1) mean evapotranspiration in case of the traditional agricultural practice E and soil mulching E_m are almost the same for the Bezenchuk and Ershov stations. The difference between them is within the accuracy of the calculation method. The evapotranspiration of the mulched soil of the Gigant and Odessa stations decreases on average by 3–4% (8–11 mm). The maximum evapotranspiration decrease by the soil mulching can be expected in Kamennaya Step (by 7% or 25 mm) and in Mironovka (by 14% or 82 mm). Mean standard deviations of the evapotranspiration for mulched soil decrease in the range from 14 (Mironovka) to 51 mm (Ershov). Under conditions of a traditional agricultural practice the range of the mean standard deviation changes between 56–78 mm. The coefficient of variation of the evapotranspiration when the soil is mulched is also significantly lower than in the conditions of a traditional agricultural practice: from 0.04 in Mironovka to 0.17 in Ershov.

CONCLUSION

The results of calculations and their analysis for the arid regions of territory under study indicate the evapotranspiration of the mulched soil does not change significantly ($E_m = E$), but the relation between the transpiration and soil evaporation (evapotranspiration structure) changes. In the wet regions, along with the change of evapotranspiration structure, the evapotranspiration of mulched soil decreases ($E_m < E$), which can result in a change of the hydrological cycle natural structure.

REFERENCES

- Agricultural ecosystems, 1987. Moscow, VO Agropromizdat, 224 pp. (In Russian.)
- Allen, H.P., 1985. Direct seeding and minimum soil treatment. Moscow, Agropromizdat, 208 pp. (In Russian.)
- Berg, L.S., 1947. Geographic zones of the Soviet Union. Moscow, Geografiz, 397 pp. (In Russian.)
- Berg L. S., 1952: Geographic zones of the Soviet Union. Vol. 2. Moscow, Geografiz, 510 pp. (In Russian.)
- Budagovskiy, A.I., 1964. Soil water evapotranspiration. Moscow, Nauka, 242 pp. (In Russian.)
- Budagovskiy, A.I., Grigoreva, N.I., 1991: Ways of increasing the efficiency of the use of soil water resources. *Vodnye resursy*, 1, 131–142. (In Russian.)
- Budagovskiy, A.I., Novák, V. 2011. Theory of evapotranspiration: 1. Transpiration and its quantitative description. *J. Hydrol. Hydromech.*, 59, 1, 3–23.
- Budagovskiy, A.I., Novák, V., 2011. Theory of evapotranspiration: 2. Soil and intercepted water evaporation. *J. Hydrol. Hydromech.*, 59, 2, 73–84.
- Budagovskiy, A.I., Shumova, N.A., 1976. Methods of the analysis of the structure of the evapotranspiration and estimates of the efficiency of its control. *Vodnye resursy*, 6, 83–98. (In Russian.)
- Dzhogan, L.YA., Gusev, E.M., 2003: Mulching effect on water supply and the spring wheat crop yield in the central and southern regions of the East European Plane. *Pochvovedenie*, 11, 1371–1382. (In Russian.)
- Gusev, E.M., 1993: Formation of the regime and soil water resources in the winter-spring period. Moscow, Fizmatlit, 160 pp. (In Russian.)
- Gusev, E.M., Dzhogan, L.Ya., 2000. Methodology of assessing the influence of soil mulching with plant residues on the formation of the water regime of the agroecosystems. *Pochvovedenie*, 11, 1403–1414. (In Russian.)
- Novikova, N.M., Nazarenko, O.G., 2007. Modern hydromorphism: processes, forms, display, and signs. *Aridnye ekosistemy*, 13, 33–34, 70–82. (In Russian.)
- Shumova, N.A., 1994: The leaf area index and evapotranspiration from spring wheat crops. *J. Hydrol. Hydromech.*, 42, 4–5, 297–314.
- Shumova, N.A., 1997. Generalize estimates of the effectiveness of the agrohydrological methods of the soil water management. Proceedings of the conference of management of landscapes disturbed by channel incision, Oxford Campus, The University of Mississippi, 433–438.
- Shumova, N.A., 1999. Validation of a model for estimation of the available soil water storage. *J. Hydrol. Hydromech.*, 47, 2, 103–116.
- Shumova, N.A., 2000. Approach and evaluation of soil water resources in an arid region of the European steppe zone territory. *J. Hydrol. Hydromech.*, 48, 6, 381–398.
- Shumova, N.A., 2009. Crop water supply and its relation to yield of spring wheat in the south of Russian plane. *J. Hydrol. Hydromech.*, 57, 1, 26–39.

Received 2 November 2011

Accepted 19 June 2012