Calculation features of evaporation from the agrocoenosis soil surface at drip irrigation and fine dispersion sprinkling

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Abstract. To define the strategy for the reclamation measures management, as well as to evaluate their effectiveness, the authors proposed to use simulation methods of the soil-plant-atmosphere system based on accumulated domestic and foreign experience and experimental material obtained from early potato plantings in the Volgograd region. The main factor affecting the yield of agrocoenosis is the moisture availability to the plant in the soil layer occupied by roots, and therefore, special attention should be paid to evaporation and transpiration modeling, and the movement of moisture in the soil profile during the irrigation (drip and sprinkling) and precipitation. The article describes the algorithm for calculating water exchange. The mathematical model is implemented by using standard Microsoft Excel software, which makes it accessible and simple enough for the user.

1. Introduction

In the «POTATO» dynamic model, the developing agrocoenosis of early potatoes is simulated from the «planting» phase to the «technical ripeness of tubers» phase and, depending on the soil moisture in the root zone and the meteorological conditions estimated by air temperature and evaporation, irrigation using drip line or fine sprinkling is recommended. The model allows to control the development of sowing and the formation of a tuber crop in situations where the production process can be limited by a supply of soil moisture and elements of mineral nutrition, structural components of a potato bush (leaf area, root depth, etc.) and weather factors. Central to the model is the calculation of the soil water balance in the irrigated area. The water flow to the leaf surface (interception), to the soil with precipitation and irrigation, moisture evaporation from the soil surface (evaporation) and the aerial parts of plants, moisture removal by roots as the result of leaf transpiration, as well as possible surface and infiltration runoff are taken into account.

Earlier, we noted that the structure and functional blocks of the «POTATO» model are based on publications by scientists who made a significant contribution to modeling agroecosystems and ecological physiology of plants (E.P. Galyamin, R.A. Poluektov, H.G. Tooming, Yu.K. Ross, C.T. de Wit, A.G. Lorch, A.I. Korovin) [1,2]. To calculate the water exchange of developing agrocoenosis, irrigated by using drip irrigation system and fine dispersion sprinkling, we thought it rational to use...
the practical approach proposed by the American agrophysicist J. Ritchie for continuous sowing crops. In particular, this approach involves a separate calculation of evaporation from the soil surface (evaporation, \( E_0 \)), moisture extraction by plant roots and its removal by leaves into the atmosphere (transpiration, \( E_p \)). The algorithm allows to calculate evaporation from a «clean» soil surface, before sowing crops, during the period from sowing to emergence of seedlings, and further, as the leaves’ area increases and they complete close [3].

As in most other dynamic models of agrocoenosis, the Ritchie algorithm uses such an intense characteristic as potential evaporation \( E_0 \) in calculations of water exchange, it is calculated by the H.L. Penman equation [4], in which the radiation balance takes into account the soil and crop albedo depending on the area of the plants projective cover. For this, the empirical equation is used: the albedo of the agrocoenosis is recounted daily, taking into account the fraction of the area occupied by plants, along with the increase in leaf mass, the agrocoenosis albedo value changes at the moment of sowing from the soil albedo to the crop albedo (in case of reaching a leaf index that provides 100% projective coverage). Assuming that the wind function and air moisture deficit influence on the moisture evaporation from the soil surface partially covered by plants is insignificant, a characteristic of potential evaporation for the soil surface \( E_{os} \) is introduced, in which, as for potential evaporation from the entire agrocoenosis, the soil radiation balance is separately calculated under vegetation.

2. Materials and methods

As in most other dynamic models of agrocoenosis, the Ritchie algorithm uses such an intense characteristic as potential evaporation \( E_0 \) in calculations of water exchange, it is calculated by the H.L. Penman equation [4], in which the radiation balance takes into account the soil and crop albedo depending on the area of the plants projective cover. For this, the empirical equation is used: the albedo of the agrocoenosis is recounted daily, taking into account the fraction of the area occupied by plants, along with the increase in leaf mass, the agrocoenosis albedo value changes at the moment of sowing from the soil albedo to the crop albedo (in case of reaching a leaf index that provides 100% projective coverage). Assuming that the wind function and air moisture deficit influence on the moisture evaporation from the soil surface partially covered by plants is insignificant, a characteristic of potential evaporation for the soil surface \( E_{os} \) is introduced, in which, as for potential evaporation from the entire agrocoenosis, the soil radiation balance is separately calculated under vegetation.

Evaporation from the soil surface is calculated in two stages: the 1-st stage is for the case when the evaporation process is limited only by the arrival of solar energy (the moisture content in the upper soil layer is high); the 2-nd stage - evaporation is limited by the moisture influx to the surface, and its speed is determined by the hydrophysical properties of the soil and moisture. The procedure for evaporation calculating begins with determining the presence of rain at the current date and the amount of moisture in the upper soil layer. If there are precipitations or irrigation in the form of rain, then the total daily evaporation from the soil surface is estimated by the ratio:

\[
E_{S1} = \min(E_{os}, U),
\]

where \( U \) is the maximum amount of possible moisture removal from the upper soil layer, which evaporation is limited by the energy input; \( E_{S1} \) is the daily moisture evaporation during the first stage of evaporation, mm.

The evaporation amount for the period of the first stage \( (\Sigma E_{S1}) \) is taken into account, and if it exceeds the maximum \( U \), evaporation is calculated according to the rule of the second stage. Thus, the inequality \( \Sigma \text{E}_{S_1}(i) \leq U \) is checked daily and, when performed, the calculation of evaporation by the rule of the first stage continues, i.e.:

\[
\Sigma E_{S1} = \Sigma E_{S1} - P + \min(U,E_{os}),
\]

where \( P \) is precipitation or irrigation by sprinkling on the \( i \)-th day, mm.

If the sum \( \Sigma E_{S1} \) becomes larger than \( U \), then the evaporation is calculated according to the algorithm of the second stage, in which the moisture removal from the soil \( (2E_{S2}) \) is determined by the soil moisture and hydraulic properties. According to the rule deduced by Black for the evaporation process
limited by soil hydraulic conductivity, the amount of moisture evaporation from the soil is represented by (3):

$$\sum_{i=1}^{I} E_{S_i}^1(i) = \alpha \cdot i^{1/2},$$

where $\alpha$ is the characteristic of soil properties (moisture conductivity), for loamy soils of the Nizhneje Povolzhje region it is 4.04 mm / day $^{1/2}$ for moisture-saturated soil, with a moisture pressure of 0.1 bar/cm [5]; $i$ is the number of days from the beginning of the soil drying second stage process when saturated with moisture in the lower horizons of the soil. Then the evaporation per day can be calculated by the difference:

$$E_{S_i}^1(i) = \alpha \cdot (i - 1)^{1/2} - \alpha \cdot (i)^{1/2}.$$ (4)

Based on the soil root layer properties data obtained during the field experiments (water-physical properties, mechanical composition, agrochemical parameters, profile morphology), the entire soil horizon ($Z$) is divided into a number of homogeneous layers according to the morphological description. The number of layers can be set arbitrarily in accordance with the available data on soil properties by horizons or in accordance with the standard breakdown used in measurements of moisture by layers. The sum of all soil layers horizons specified in the model should be larger than the layer occupied by plant roots. The thickness of the top layer should not be more than 100 mm. For each soil layer, the characteristics of the particle size distribution and the water-physical properties of the experimental plot soils should be determined. The root system of “Impala” early potato varieties reaches a maximum depth of 0.8 meters; therefore, in the experimental plot, soil samples were taken for analysis to the depth of 0.8 m.

For effective use of the Ritchie algorithm the thickness of the upper layer is equal to:

$$z_0 = \frac{U}{(\Theta_{sat} - \Theta_{res})},$$

where $z_0$ is the thickness of the upper layer, mm; $U$ is the limited amount of moisture evaporating at the evaporation process first stage, mm; $\Theta_{sat}$, $\Theta_{res}$ is the volumetric moisture content in the upper soil layer at saturation and at the soil air hygroscopicity, respectively, mm$^3$/mm$^3$. In the balance calculations, soil moisture is presented in two dimensions: units of volumetric moisture (mm$^3$/mm$^3$) are used to describe the specific content of available moisture ($w$); relative units ($\Theta/\Theta_{sat}$) in fractions or % of minimum water capacity ($W$) are used in functions and for displaying on graphs.

3. Results
When the drip irrigation method is appointed, the value of potential evaporation does not change in the evaporation calculations, the topsoil maintains its moisture, and the water coming from the dripper fills the second and others underlying horizons. In this case, the evaporation from the soil calculation is performed according to the algorithm of the first or second, less intense, evaporation phase. The results of numerical experiments for the potatoes evaporation and transpiration calculating during the irrigation by using sprinkling and drip irrigation (the same irrigation rates, soil and weather conditions) are shown in the figure 1.
Figure 1. Potato plantings evaporation and transpiration intensity dynamics, calculated on the «POTATO» model during sprinkling and drip irrigation for weather conditions in 2015.

Using the proposed method capabilities, due to the evaporation and transpiration separate calculation, when finely dispersed sprinkling is recommended, an experimentally verified assumption is introduced to reduce the potential evaporation by the amount sprayed by using finely dispersed sprinkling over the water area in mm (for the conditions of the Volgograd region), which is taken into account in the evapotranspiration calculations agrocoenosis.

Figure 2. The results of experimental data and simulation calculations on the soil water balance (m³/ha) for the vegetation of early-ripe potatoes in 2015 according to the field experiment options: (A - irrigation method: A1 - drip, A2 - combined; B - irrigation regime according to development phases; C - fertilizers doses: C1 - N₁₆₀P₃₅K₆₄, C2 - N₂₁₅P₁₁₇K₁₇₄, C3 - N₂₇₀P₁₄₄K₂₈₄).

According to the same principle, the J. Ritchie algorithm takes into account precipitation in small quantities (1-3 mm). The results of the soil water balance calculations for all the experimental options during the drip and combined irrigation methods (drip irrigation and fine dispersed sprinkling) show that the observed patterns of moisture use efficiency for various irrigation methods differ, as it is shown in the figure 2 and the table 1.
| Experiment option | Calculation on the model «POTATO» | Actual observations | Calculation | Observations | The difference between actual and estimated balances, m³/ha |
|-------------------|-----------------------------------|---------------------|-------------|--------------|---------------------------------------------------------|
| A1B1 C1           | 1898 2090 3988 1623 2000 - 3623 500 387 113 | 382 118 5 | | | |
| A1B1 C2           | 1899 2089 3988 1623 2000 - 3623 500 385 115 272 228 11 3 | | | | |
| A1B1 C3           | 1855 2175 4030 1623 2000 - 3623 500 348 152 112 388 23 6 | | | | |
| A1B2 C1           | 1735 2441 4176 1623 1800 - 3423 500 243 256 242 258 2 | | | | |
| A1B2 C2           | 1684 2587 4271 1623 1800 - 3423 500 199 300 182 318 18 | | | | |
| A1B2 C3           | 1644 2671 4315 1623 1800 - 3423 500 172 327 122 378 51 | | | | |
| A1B3 C1           | 1764 2299 4063 1623 1700 - 3323 500 261 239 152 348 10 9 | | | | |
| A1B3 C2           | 1706 2449 4155 1623 1700 - 3323 500 213 286 102 398 11 2 | | | | |
| A1B3 C3           | 1666 2549 4215 1623 1700 - 3323 500 177 323 42 458 13 5 | | | | |
| A2B1 C1           | 2027 1979 4066 1623 2200 237 4060 500 537 -38 634 -134 -96 | | | | |
| A2B1 C2           | 1989 2061 4050 1623 2200 237 4060 500 502 -3 620 -120 -11 7 | | | | |
| A2B1 C3           | 1919 2189 4108 1623 2200 237 4060 500 466 34 460 40 6 | | | | |
| A2B2 C1           | 1798 2456 4254 1623 2000 243 3866 500 362 138 425 75 -63 | | | | |
| A2B2 C2           | 1732 2600 4332 1623 2000 243 3866 500 329 171 375 125 -46 | | | | |
| A2B2 C3           | 1676 2727 4403 1623 2000 243 3866 500 291 208 344 156 -52 | | | | |
| A2B3 C1           | 1833 2302 4135 1623 1900 243 3766 500 404 96 345 155 59 | | | | |
| A2B3 C2           | 1772 2435 4207 1623 1900 243 3766 500 351 149 305 195 46 | | | | |
| A2B3 C3           | 1694 2610 4304 1623 1900 243 3766 500 300 200 274 226 26 | | | | |

During combined irrigation the soil moisture use by a plant is lower than at drip irrigation; this is primarily due to the irrigation rate increase because of the growing season lengthening, and the use of fine dispersed sprinkling, which affects transpiration (decrease). The mineral nutrition extra doses
application increases water consumption at drip and combined irrigation. The water regime
dependence on the fertilizer application level is caused by the root system and the plant aerial parts
development, as well as a photosynthetic potential increase. The plants use soil moisture more
efficiently while combined irrigation and the fine dispersed sprinkling application.

4. Conclusion
Evaporation and transpiration are calculated by using the Ritchie algorithm modified by us, in which
the moisture input to the soil by drip irrigation provides the topsoil maintaining possibility in the dried
state and its albedo, as well as taking into account the fine dispersed sprinkling in the water balance of
agrocoenosis as the precipitation interception on the vegetation cover, leading to a daily volatility
decrease. The underlying layers moistening during the precipitation and irrigation filtering is specified
according to the rule in which the soil layers are filled with water successively (from the top to the
bottom and further down) only to the lowest moisture capacity value.

Evaporation calculations include additional albedo parameters for dry and moist soil, the area of
the evaporating surface, its value is associated with the planting method and the seedbed geometric
characteristics.

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